Repurposing Technology: An Innovative Low Cost Two-Dimensional Noncontact

Measurement Tool

by

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ABSTRACT

Two-dimensional vision-based measurement is an ideal choice for measuring small or fragile parts that could be damaged using conventional contact measurement methods. Two-dimensional vision-based measurement systems can be quite expensive putting the technology out of reach of inventors and others. The vision-based measurement tool design developed in this thesis is a low cost alternative that can be made for less than $500US from off-the-shelf parts and free software. The design is based on the USB microscope. The USB microscope was once considered a toy, similar to the telescopes and microscopes of the 17th century, but has recently started finding applications in industry, laboratories, and schools. In order to convert the USB microscope into a measurement tool, research in the following areas was necessary: currently available vision-based measurement systems, machine vision technologies, microscope design, photographic methods, digital imaging, illumination, edge detection, and computer aided drafting applications. The result of the research was a two-dimensional vision-based measurement system that is extremely versatile, easy to use, and, best of all, inexpensive.

DEDICATION

This thesis is dedicated to the friendship and memory of

Patricia Anne McAllister Moffatt.

1942 – 2011

ACKNOWLEDGEMENTS

This thesis took almost a year to complete. The first few months were spent proving that designing and building an inexpensive two-dimensional noncontact measurement tool was a feasible Master's thesis topic. My thesis committee, I think, was a bit dubious about my proposed subject, but they went along with it. After that came several months of research, reverse engineering, dead ends, obstacles, and failed experiments.

This last year was not much fun. It felt more like I was stumbling along in a dark tunnel not knowing if there would actually be light at the end. Along the way I encountered people who made my research very difficult and my time at ASU a horrible experience, but there were others who made the ordeal a little easier. I would like to thank the following:

My Thesis Committee: Professors Russell Biekert, Narciso Macia and Robert Meitz for not trying to steer my thesis research or make ridiculous demands. I would also like to thank them for their kind words of encouragement.

Professor Daniel Wilson for introducing me to the concept of disruptive technology. It took almost a year to figure out how to integrate the concept into my thesis.

Mesa Community College instructors: Scott Shaw and Keith Evanson. Their enthusiasm about engineering and design made me decide to go for the Master's degree.

Most of all, I would like to thank my husband, Steven L. Graham, for his support, patience, and welding skills.

TABLE OF CONTENTS

CHAPTER Page

APPENDIX Page

LIST OF FIGURES

FIGURE Page

FIGURE Page

LIST OF TABLES

TABLE Page

TABLE Page

PREFACE

In this preface I give a brief account of how this thesis came about. Learning about two-dimensional noncontact measurement was not my first choice of topic for a Master's thesis. It was research born out of necessity. I was interested in the process of using reverse engineering as a tool for new product design and thought the best way to learn about the subject was to take something apart and then improve its design. I selected the ubiquitous wind-up music box because of its cylindrical musical movement. Music box movements have very small parts that are not easy to measure. I couldn't find the measuring equipment or the expertise I needed for my project at the university so I decided to make my own tools instead. It turned out that the research involved in understanding how noncontact measurement worked and how it could be used for measuring small parts was just as much an exercise in reverse engineering and machine design as the music box would have been.

Having a very limited budget made researching, designing and developing the two-dimensional noncontact measurement tool a real challenge. Not wanting to waste anything I decided that the tool had to repurpose existing technology. To repurpose means to use an existing item in a new way. Repurposing technology is also a theme in disruptive innovation. The tool researched and designed in this thesis is an example of a low end disruptive innovation, which according to Clayton M. Christensen, author of The Innovator's Dilemma, is a novel combination of existing off-the-shelf components and designed for the least profitable customer who would be happy with a "good enough" product, and is unwilling to pay for product enhancements.

The result of this research was an inexpensive, easy to use tool that I hope will get more people excited about digital noncontact measurement technology. The tool was designed so that when it was no longer needed it could be disassembled and the parts used in other applications.

1. INTRODUCTION

Humans have been using noncontact measurement methods since the beginning of time. The use of fingers and hand widths to estimate how far away or how big an object is the most common method. Over the centuries other noncontact measurement tools have been developed, but mostly for measuring long distances or large shapes such as buildings.

But what about measuring really small objects? The first microscope was invented by Zaccharias and Han Janssen in the late 1590s. Early microscopes had low magnification and were difficult to focus. Getting the light just right in order to see a specimen was very difficult. They were treated more like toys than the latest in scientific instrumentation. A few microscopes fell into the hands of serious scientists. The evolution of the microscope that we see today was a very slow process with several lengthy gaps between improvements.

The first paradigm shift in the way we looked at the world took place when photography was invented in the early 19^{th} century. By the 1850s photographic methods were being used by artists, scientists, inventors, and entrepreneurs in new ways. Its usefulness was limitless. By the end of the century two new subfields of photography emerged: photogrammetry and photomicrography. Photogrammetry was developed as a way to determine measurements of objects from photographs. Photogrammetry became very popular as a means of measuring landscapes. Photomicrography is the practice of taking pictures through a microscope. For scientists this was a godsend. It eliminated the need to make hand drawn sketches of what they had seen.

The second paradigm shift was digital imaging. While digital imaging technology had been around since the 1950s, but it wasn't until the mid-1990s that it became available to consumers. Photogrammetry and photomicrography professionals immediately jumped on the bandwagon. Now they had images that could be directly input into computer programs for analysis. The next generation of noncontact measurement tools was about to begin.

In the mid-1990s Hemmlab, Albertz, Schubert, Manfred, Kohler, and Michael (1996) authored a paper describing their work in developing photogrammetric methods for three-dimensional microstructures. A little later, Mitchell, Kniest, and Won-Jin (1999) presented a report on applying commercial digital photogrammetry principles to photographs generated via stereo microscope. The case studies presented in this thesis provide additional examples of digital close range and microscopic photogrammetry.

Noncontact measurement encompasses any sort of measurement that is performed without making contact. Both digital microscope photogrammetry and machine vision technologies are in this category, but they solve different problems: Machine vision, an engineering field that utilizes digital imaging for industrial and manufacturing problems, Machine vision is ideal for high volume and continuous volume manufacturing. The hardware and software used are designed to analyze images at high speeds. Digital microscope photogrammetry is designed for research.

Digital microscope photogrammetry equipment is quite expensive because it is very specialized. The manufacturers of the equipment utilize custom hardware and proprietary software. Research revealed that the hardware and software components needed to develop a “low-end” version were readily available. The objective of this thesis is to describe the research and reverse engineering that was necessary in order to design and develop a low cost Two-Dimensional Noncontact[1] Measurement Tool (2DNCMT) (see Figure 1.1) for measuring small[2] and micro parts using off-the-shelf components and open source software for less than $500US.

[1] In this thesis the words “noncontact”, “digital microscope photogrammetry” and “vision-based” have the same meaning and are used interchangeably.

[2] In this thesis a small part is less than 0.5 inch in diameter. A Micro part is less than 0.01 inch in diameter.

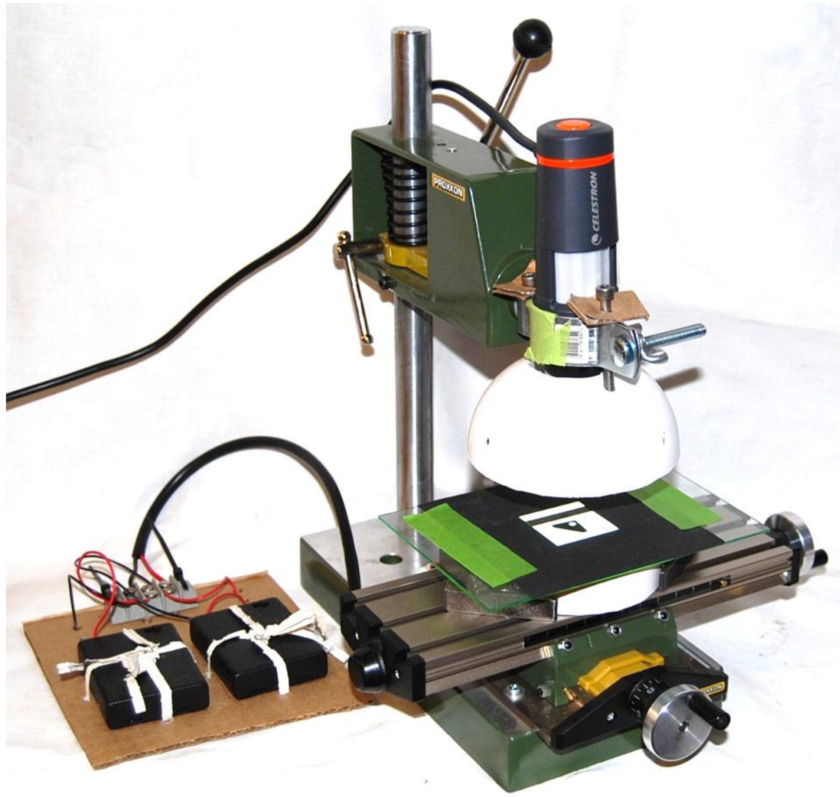

Figure 1.1 Completed Two-Dimensional Noncontact Measurement Tool

The 2DNCMT presented in this paper is a “low-end disruptive innovation” in that it is a novel combination of existing off-the-shelf components and designed for the least profitable customer who would be happy with a “good enough” product, and is unwilling to pay for product enhancements. In order to do this the tool had to be designed to be easy to repair, upgrade, and customize by the user and could not be reliant on a specific manufacturer or software application. The end product would be a tool that users could modify to fit their needs, upgrade when improved technology becomes available, and repair by making a trip to the local hardware or computer store. The tool described in this paper was designed to meet the needs of potential users of vision-based measurement technology such as:

- Tinkerers, inventors, and others who sometimes need cost effective ways of solving measurement problems.

- People interested in the technology but do not have access to vision-based measurement tools normally found in commercial and university metrology laboratories.

- Companies considering adding vision-based measurement methods to their inspection process but want to learn more about it before purchasing what might be very expensive piece of measurement equipment.

The heart of this project was the inexpensive USB microscope. The USB microscope started out as a throw-away electronic gadget made for the Chinese market. It was never expected to be anything but a toy. It did not take long before people realized that it worked well as an inspection tool and now it is being used in engineering and science labs. Tormach, LLC, a manufacturer of small CNC mills, offers the USB microscope as part of their CNC Scanner module. Keyence Inc, a major manufacturer of high-end optical equipment, offers a digital microscope that utilizes similar technology. USB microscopes can be purchased for as little as $60US. Even low-end models like the one used in this research, can be utilized as two-dimensional vision-based measurement tools.

The 2DNCMT has components in machine design, illumination, imaging methods, software and dimensional metrology. Figure 1.2 illustrates this relationship.

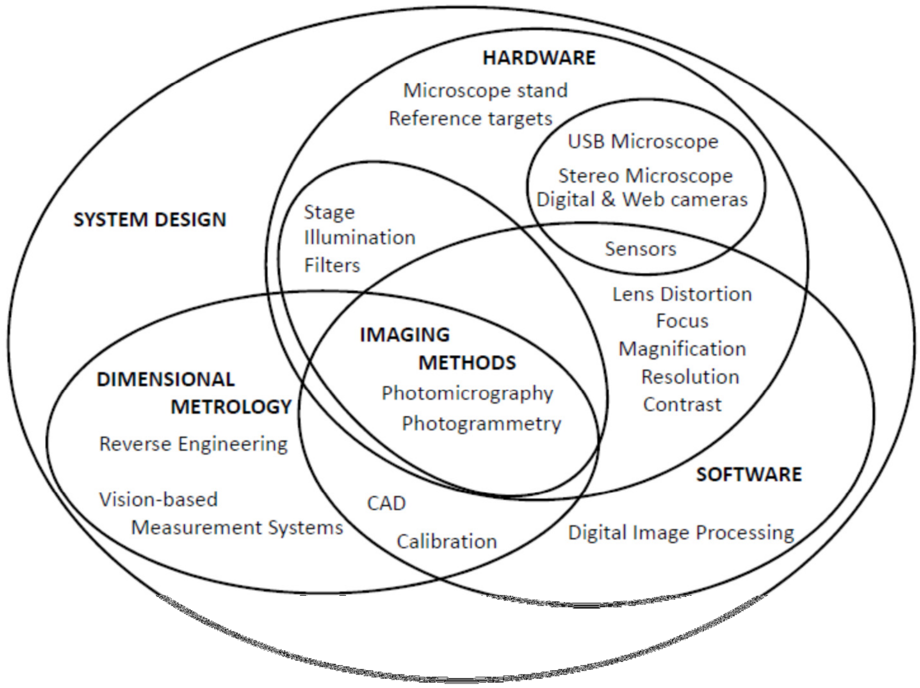

Figure 1.2 Research Topic Relationships

The hardware ultimately selected for the 2DNCMT was repurposed from consumer quality off-the-shelf components. Some parts required slight modifications using household tools. Research on current vision-based measurement technology proved to be useful when developing the USB microscope support design, reference targets, and illumination.

Software for the 2DNCMT was selected from a large group digital image enhancement software packages. While images made by the 2DNCMT can be manipulated with popular software such as Adobe Illustrator and AutoCad, the budget dictated that free or nearly software was to be used instead.

Determining the best mechanical and software techniques for generating good images and converting those images into Design Exchange Format (DXF) format was a challenge. Some of the factors that affected the outcome were: the perpendicularity of the camera to the part surface being measured, the cleanliness, color and surface texture of the part and the reference target type, the thickness of the part, illumination, temperature, humidity, and operator experience. Understanding the relationships between the machine design, illumination, digital imaging methods and software, and dimensional metrology helped bring this project together.

The 2DNCMT is not only a measurement tool. It can also be used for macro photography and non-dimensional inspection processes. The way the tool is designed makes it extremely versatile. For example, the USB microscope, which is the heart of the system, can be disconnected from its support and used to inspect and measure objects that won't fit on the specimen stage. The software may be used independently as well.

Engineering is not just about designing new products and processes that have never existed before. It is also about using existing products in new ways. This project was no exception. All of the hardware and software used in this project was originally designed for other applications.

THESIS ORGANIZATION

Table 1.1 provides information about the organization of this thesis and its appendices.

Table 1.1

Thesis Outline

Chapter	Description
2	Research performed in order to understand two-dimensional vision-based measurement technology including five case studies.
4	Research necessary for designing and building the 2DNCMT.
5	Verification and analysis of tool design and tool measurement capability.
6	Conclusion

Appendix	
A	2DNCMT Budget and Bill of Materials
B	2DNCMT Machine Build
C	Design Data. Dimensioned drawings for parts that required modification.
D	Contains measured test part drawings, measurement data for the parts from on the 2DNCMT and the Nikon VMA-2520, the control system used in this project, and Gage R&R results.
E	2DNCMT Operating Procedure.
F	Software Analysis. Software research information.
G	Detailed information on USB and light microscope design.
H	Lighting System Analysis and Design
J	Image analysis including high contrast and histogram studies
K	Difference between CCD and CMOS technology
L	Feasibility Studies and Results
M	Engineering Notes. This appendix is a catch-all for design notes, process development, and other items of note that do not fit anywhere else in the document.

2. LITERATURE REVIEW

The objective of this thesis project was to design and build a very basic, manually operated two-dimensional noncontact measurement tool designed for less than $500US for accurately measuring parts or features smaller than 0.5 inches in diameter. The original intent for this novel 2DNCMT was reverse engineering small parts. As the research progressed it became obvious that the proposed 2DNCMT could be useful in other applications as well.

Before the 2DNCMT design could be started research in the following areas was needed: vision-based measurement systems, microscope design, photographic methods, digital imaging technology, illumination, edge detection, and computer aided drafting (CAD) applications. Table 2.1 outlines the contents of Chapter 2 and the research performed in order to understand two-dimensional vision-based measurement technology.

Table 2.1

Chapter 2 Outline

Section	Title	Description
2.1	Vision-based measurement Systems	Introduction to the concept of vision-based measurement, its relationship to machine vision.
2.2	Photographic Methods	History of photogrammetry, macrophotography, and photomicrography. Edge detection algorithms used in the raster to vector conversion process.
2.3	Hardware	Stereomicroscope design. Digital camera technology Lenses, sensors, filters, zoom, crop-frame sensors, shutters, and zoom. Illumination techniques for stereo microscopes and machine vision.
2.4	Software	Digital imaging software topics A brief history of Computer Aided Design and its relationship to this project.
2.5	Case Studies	Examples of vision-based measurement systems and research.

MACHINE VISION AND VISION-BASED MEASUREMENT SYSTEMS

There are two types of synthetic vision: machine and computer. Machine vision is an engineering discipline focused on industrial and manufacturing problems and is associated with computer science disciplines such as computer vision, equipment control, databases, networking, machine learning and interfacing. Computer vision is focused on artificial vision and mimicking human or animal visual capabilities (Pham & Alcock, 2003). This thesis focuses on machine vision.

Machine vision was first offered as a technology for manufacturing automation in the early 1980s. Semiconductor and electronics manufacturers were the first to adopt the technology and now they account for more than half the machine vision applications on the factory floor. Since then, machine vision has been introduced to food processing, pharmaceuticals, plastics, metal working, and other industries. Progress in the machine vision field has come with growing pains, mostly in the hardware and software controls (Fabel, 1997).

Machine vision systems use a combination of video cameras and computers to convert light energy into a digital image. The images are used to calculate part orientation or measurements. Machine vision reigns supreme in finding and examining objects with hard, well-defined edges and regular patterns (Fabel, 1997) (Ross, Fardo, Masterson, & Towers, 2011).

Vision-based measuring systems are designed to make highly accurate measurements without physically contacting the part being tested. These systems are a hybrid mix of personal computers, video cameras with Charge Coupled Devices (CCD) or Complementarity Metal Oxide Sensors (CMOS), Coordinate Measuring Machines (CMM), robots, and measuring microscopes. They utilize edge detection and shape memorization algorithms for detecting and measuring shapes (Dhandayutham, 2005). Image analysis for inspection is commonly used to collect and record dimensional measurements. This provides a nondestructive method of quality control testing (Ross, Fardo, Masterson, & Towers, 2011).

Typical uses for vision-based measuring systems are: automated inspection for high volume production, optical character recognition and other non-contact applications. How machine vision metrology is used varies, but the problem is essentially the same: how do you acquire images that place a pair of pixels on the smallest possible feature, while covering a relatively large area compared to the minimum critical dimension (Hardin, 2010) (Bridgefield Group, 2010).

Today, machine vision technology is inexpensive and so prevalent in everyday activities that it is literally taken for granted. The market is flooded with low-cost imaging devices such as digital cameras, video cameras, and microscopes. According to Spicer, et al (2005) these devices are capable of performing the same industrial inspection tasks as their more expensive, less user friendly, industrial counterparts but with a little less accuracy. These devices are also starting to take the place of traditional contact measuring tools. Jeff Corey, ATEK Medical (Morey, 2011), observed that “a single system has the ability to replace multiple gadgets, eliminate calibration time, processing cost, and redundant capital expense.”

Vision Measurement Accuracy. Vision measurement accuracy depends on image quality and the correlation between feature size and pixel resolution. The features that control these attributes are: optical lens quality, image sensor type and capability, image format, and color interpretation (Doverspike, 2011).

Problems with Vision-Based Measurement. At the time this research was taking place, there were no standards for vision-based measurement systems. ISO/CD 10360-8 was the latest proposed standard for three-dimensional imaging and scanning, but it was being met with resistance from both manufacturers and user because it attempted to apply CMM standards to scanners. One of the problems was that CMM procedures are limited to measuring simple objects, but most users of vision-based measurement equipment were more interested in measuring deep holes, edges, corners, surface textures, and micro parts. (Pfeffer, 2011)

The goal of any standard is to provide a method for users to evaluate if a product or process performance meets their needs. Chuck Pfeffer (2011) commented in his editorial in Society of Manufacturing Engineers magazine that “manufacturers of vision-based measuring equipment provide little in the way of test results especially when it comes to accuracy. Customer demand is the best way to remedy this situation.”

This problem isn’t new, Michael Neeves (1998) noted that “the metrological world accepted the faults of vision and continued to measure incorrectly. The evolutionary changes occurring in production were not incorporated into metrology inspection systems.” Metrology labs have accepted the fact that their vision systems measure in two dimensions and that they don’t measure to the datums. Measurement inaccuracies have been accepted by metrologists, who have compensated by developing an excuse mentality for their vision systems. Such an attitude is dangerous and, quite frankly, inexplicable. The lack of standards left many metrology labs with vision-based measurement equipment relegated to gadget status because there was no way to properly evaluate it (Neeves, 1998).

PHOTOGRAPHIC METHODS

The following photographic methods employed by vision-based measurement tools are described in this section:

- Photomicrography. Taking images through a microscope.
- Photogrammetry. The practice of determining the measurements or geometric properties of objects from photographic images (Walford, 2007).
- Microscopic Photogrammetry. Applying photogrammetric methods to images taken through a microscope.

Photomicrography. Photomicrography is the practice of taking pictures through a microscope. It is not microphotography, which involves microfilm and other miniature images; nor is it macrophotography which is generally the production of close up photos taken within a foot or less (Digital SLR Photography, 2006).

Photomicrography is the art of capturing images using a microscope. Early photomicrograph images were remarkably high quality, but very labor intensive. Until the 1990s film was the primary medium, but digital imaging has made photomicrography cheap and easy (Abramowitz, Spring, Flynn, Long, Tchourioukanov, & Davidson , 2011). Figure 2.1 shows early photomicrographer Arthur Smith demonstrating the bellows extension needed to project an image onto a 12x10 photographic plate (Walker, 2010).

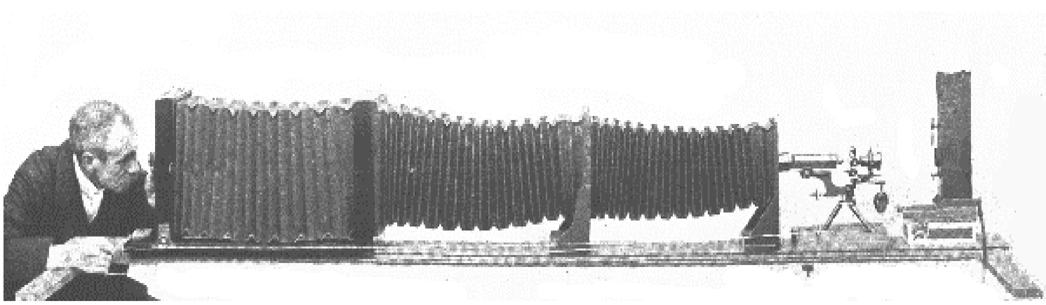

Figure 2.1 Early Example of a Universal Photomicrograph Apparatus

Whether a film or digital camera is used, the quality of a photomicrograph is completely dependent on three factors: the quality of the equipment used (microscope, camera, lighting); precise sample preparation; and the skills of the microscopist (Partin, 2010).

Photogrammetry. Photogrammetry is the practice of determining the measurements or geometric properties of objects from photographic images. The end result is a scaled map, drawing, or a 3D model of a “real-world object or scene” (Walford, 2007).

The art of photogrammetry, or metrophotography as it was originally termed by its inventor Aimé Laussedat (1851), was developed to be able to find the correct metrical representations of the object photographed from ordinary photographs (Ahmed & Haas, 2010). Photogrammetry can trace its roots back to 1038 when Al Hazen explained the principles of the camera obscura (dark room) and binocular vision. Leonardo Da Vinci (1490) expanded the definition by including the concepts of perspective and projective geometry. Johan Heinrich Lambert (1759) developed the mathematical principles of a perspective image to find a point in space. After 1850, there have been four distinct development cycles in photogrammetry (Burtch, Robert , 2011): 1850-1900, Plane Table Photogrammetry; 1900-1960. Analog photogrammetry; 1960-present, Analytical Photogrammetry; and now, Digital Photogrammetry.

There are three basic types of photogrammetry:

- Aerial. A series of photographs of an area of terrain in sequence using a precision camera. The camera may be in an aircraft, hot air balloon, remote control aircraft, etc.
- Terrestrial. Photos are taken from a fixed and usually known position on or near the ground with the camera axis horizontal or nearly so. Architectural photogrammetry is an example of this type.
- Close range. A camera is placed close to object being observed. This method is most often used when direct measurement is impractical.

Microscopic Photogrammetry. Microscopic photogrammetry, a subfield of close range photogrammetry, is the process being used for scaling images generated in this research. Applying photogrammetric methods to microscopes is difficult due to the fact that the microscope field of view is narrow, and the depth of field, the distance between the nearest and farthest objects in a scene, is shallow. Couple those with unique image scales, and "unconventional and uncertain imaging geometry", and the need for reference targets and the task becomes more complicated (Mitchell, Kniest, & Won-Jin, 1999).

Images generated by the USB microscope in this project are raster images which can be "measured" by the pixel array produced by the array size scanned by the CCD or CMOS sensor in the microscope or other digital imaging device. It must be noted that a pixel array has no defined unit of measurement. For the USB microscope, the image needs to be calibrated each time the magnification is changed. In order to properly calibrate the image, an object with a known measurement must be included in the image; the image is then scaled to so that the known object is accurately measured; then the rest of the objects in the image may be accurately measured. In this project, calibration occurs in the 2D CAD environment. Figure 2.2 shows a ring shaped reference target being used to measure a micro part. The reference target and micro part are approximately the same thickness.

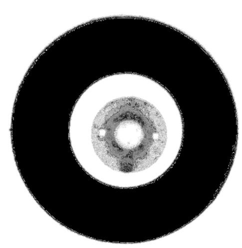

Figure 2.2 Reference Target with Micro Part

HARDWARE

In order to determine the best mechanical design for the 2DNCMT hardware research covered microscopes, digital camera hardware, illumination, lens distortion, focus, magnification, and resolution.

Stereo Microscope. The stereo microscope dates back to the late 1670s when Cherubin d'Orleans designed and built a microscope with twin eyepieces and matching objectives. His design was actually a “pseudostereoscopic system that achieved image erection only by the application of supplemental lenses.” It had a major design flaw: “The right side image was directed to the left eyepiece and the left side image was directed to the right eyepiece.” It would be over 200 years before the first true stereo microscope would be made by Horatio S. Greenough, an American instrument designer, with the help of the engineers at the Carl Zeiss Company. Greenough’s stereo microscope was, and still is, the “workhorse in medical and biological dissection.” (Nothnagle, Chambers, & Davidson, 2010)

Stereo microscopes are low power microscopes used to view whole samples or where any sort of manipulation is necessary like dissection or watch repair. Stereo microscopes use reflected illumination, where the light is reflected off the surface of the object or backlighting to develop high contrast silhouettes. In contrast, light microscopes use transmitting light, that is, shining a light through the object being examined.

Structurally, stereo microscopes may have rigid frames, as shown in Figure 2.3 (Lab Recyclers, Inc., 2011), similar to light microscopes or be mounted on a boom (Figure 2.4). They may also come with built in under-stage illumination (Figure 2.3).

Figure 2.3 Stereomicroscope with Rigid Frame and Illuminated Stage

Boom microscopes are much more versatile design than the traditional light microscope. The basic design is a stereomicroscope body mounted on a flexible, movable metal arm or a boom, as shown in Figure 2.4 (Metallurgical Supply Company, 2011). The boom allows the microscope greater Z-axis travel and 360 º rotation capability in in the XY-plane. The microscope itself also has the capable of being rotated in the XZ-plane. Boom mounted microscopes are used mostly for inspection and repair operations.

Figure 2.4 Boom Mounted Stereomicroscope

Digital Cameras. The evolution of the digital camera, web cameras and USB microscope is covered in this section. All three types may be used in the 2DNCMT design, but different software might be needed.

Consumer Digital Cameras. Digital camera technology is based on the same technology used to record television images. The video tape recorder (1951) was used to record images from television cameras by "converting the information into electrical impulses (digital) and saving the information onto magnetic tape" (Bellis, 2011). In 1972, Texas Instruments designed a filmless analog-based electronic camera but never commercialized it. In 1981, the first electronic camera offered to the public was the analog-based Sony Pro Mavica[3] (Consumer Electronics Association, 2011).

True digital cameras trace their roots back to 1969 when George Smith and Willard Boyle of Bell Telephone Labs invented the Charge Coupled Device (CCD). The CCD converts light into electrical charges in small cells or pixels and output the image as a series of numbers. The CCD was the critical first step in the evolution of digital cameras (Mirsky, 2009). During the following years, the CCD was used for a variety of applications in digital signal processing (including image processing), astronomy and laboratory analytical instrumentation. While Complementary Metal Oxide Sensor (CMOS) and CCD technologies were developed about the same time in the 1960s, CCDs became the dominant image sensors only because the technology to produce them was readily available. (Teledyne Dalsa, 2011).

In late 1975, Steve Sasson leading a team of engineers at Kodak, successfully designed and built the first digital camera using a kluge of used parts from a movie production line, "a highly temperamental new type of CCD imaging area array", and parts salvaged from electronic test equipment. The process was called "Filmless Photography" (Sasson, 2007). The next year Kodak became the first company to produce digital

[3] Mavica was a combination of the words Magnetic Video Camera.

cameras, but the technology wasn't available to consumers until the early 1990s. In 1994, the Apple QuickTake 100 camera, which only worked with Apple computers, was offered to the public. Digital cameras finally became popular in the consumer market around 2000.

Consumer digital cameras are self-contained portable computers. They have an operating system, image enhancement software, memory, and an internal power source. Consumer digital cameras are designed to be used for short periods of time in environments that are mostly clean, dry, and at a comfortable temperature (for humans).

Web Cameras. The first commercial web camera (webcam), the QuickCam as shown in Figure 2.5 (VidGuard, 2011), came on the market in 1994. The QuickCam webcam started as a graduate research project and was originally intended for used with Macintosh computers, but the company manufacturing the unit, Connectix, wanted it to work on multiple platforms. In 2000 computer manufacturers began integrating web cameras into laptop computers and computer monitors. (Blog Webcam, 2010)

Figure 2.5 Logitech QuickCam

Webcam construction commonly consists of a consumer-grade plastic lens and a CCD or CMOS sensor. Image resolution commonly falls in the 320x240 pixel range. Webcams are not stand-alone computers like consumer digital cameras. Webcams do not have built-in operating systems, image enhancement software, memory, or power supplies. They rely on a host computer for those functions. Common operating systems like Microsoft Windows, Linux, and Mac OS X have USB Video Class (UVC) drivers built in so additional software is not needed (Blog Webcam, 2010).

USB Microscope. Early USB microscopes had objective turrets similar to light microscopes. The original Brando and Mattel USB microscope designs incorporated light microscope features such as objective turrets and bright field illumination (the object is illuminated from below and observed from above). Current hand-held models are webcams with a high-powered macro lens and reflected illumination, that is, the lighting is situated above the object similar to a stereo microscope.

The first USB microscope was thought to have been designed and manufactured in 1998 by Brando, a Hong Kong-based company. Brando was known for developing odd devices and gadgets mostly for the Chinese market. Like most of their products, USB microscopes were cheap, easy to make, and not expected to last a long time. Their USB microscope (Figure 2.6) was designed as a cross-gadget to appeal to a larger audience. It was a digital microscope, but it also allowed users to take videos and still images. By many, it was and still is considered a toy, but it has also caused renewed interest in microscopy (SoftPedia, 2011) (Harper, 2000).

Figure 2.6 Brando USB Microscope

In 1999, Intel and Mattel teamed together to develop and produce the QX3 IntelPlay Plus Computer Microscope as shown in Figure 2.7 (Davidson, 2003) designed to be used as an educational toy plus introduce optics, imaging and computers to grade school children. It used a turret to switch between the 10X, 60X and 200X objectives. The QX3 was a hand-held USB microscope. It came with a base not only to make it more like a traditional microscope but also easier for children to use.

Figure 2.7 IntelPlay QX3 Plus Computer Microscope

In 2002, Scalar, a manufacturer of optical and electronic devices, came out with a more sophisticated hand-held USB microscope called the ProScope (Rubenking, 2002). Since then, hand-held USB microscopes have been finding their way into classrooms, laboratories, factories, and other places.

See Appendix G. Microscope Design for more information about USB and light microscope design.

Digital Camera Hardware. Digital cameras use a combination of scanning hardware and software to generate images. As shown in Figure 2.8: Light enters the camera through a lens. The lens is used to focus and/or magnify the image; the light is directed onto the CCD or CMOS image sensor. A mechanical or electronic shutter is used to determine how long the sensor is exposed.

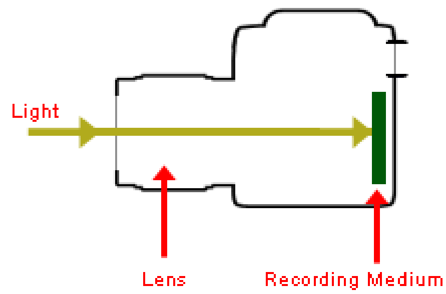

Figure 2.8 Basic Imaging Requirements

CCD and CMOS Sensors. In CCD cameras the charge is actually transported across the chip and read at one corner of the array. An analog-to-digital converter turns each pixel's value into a digital value. CCDs use a special manufacturing process to create the ability to transport charge across the chip without distortion. This process leads to very high-quality sensors in terms of fidelity and light sensitivity. “CCDs tend to be used in cameras that focus on high-quality images with lots of pixels and excellent light sensitivity.” (HowStuffWorks, 2000) The conveyor belt analogy is the best way to describe how a CCD device works. See Figure 2.8. Michael Richmond (2011), Rochester Institute of Technology, explains the Conveyor Belt Analogy as follows:

> “[A] number of buckets (Pixels) are distributed across a field in a square array. The buckets are placed on top of a series of parallel conveyor belts and collect rain fall (Photons) across the field. The conveyor belts are initially stationary, while the rain slowly fills the buckets (During the course of the exposure). Once the rain stops (The camera shutter closes) the conveyor belts start turning and transfer the buckets of rain , one by one , to a measuring cylinder (Electronic Amplifier) at the corner of the field (at the corner of the CCD).”

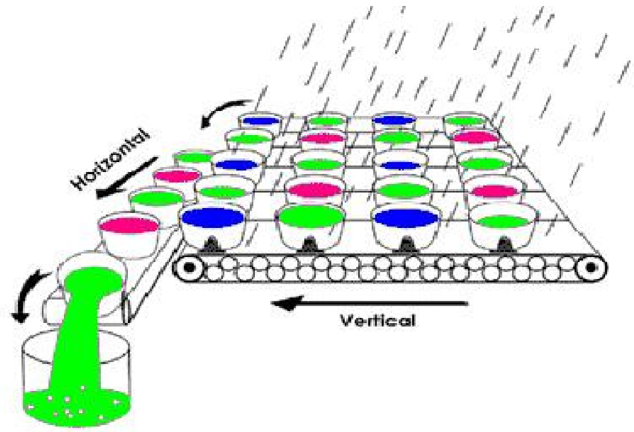

Figure 2.9 How a CCD Sensor Works

In the 1990s semiconductor lithography techniques were refined to the point that CMOS technology surpassed CCD in “lowered power consumption, camera-on-a-chip integration, and lowered fabrication costs from the reuse of mainstream logic and memory device fabrication” (Teledyne Dalsa, 2011). CMOS sensors “have several transistors at each pixel that amplify and move the charge using more traditional wires. The CMOS approach is more flexible because each pixel can be read individually.” CMOS chips use traditional manufacturing processes to create the chip; the same processes used to make most microprocessors. Recently CMOS sensors have been improving to the point where they are almost equal with CCDs in some applications. CMOS cameras are less expensive and use less energy (HowStuffWorks, 2000).

Each pixel on a CMOS device is embedded in an x-y coordinate system and can be read directly. This means a CMOS pixel always detects a photon directly, converts it into voltage, and transfers the information direct to output (Richmond, 2011).

Sensor Selection. Sensor selection is dependent on the camera manufacturer. For example: Camera makers Nikon and Canon use mostly CMOS in Digital Single Lens Reflex (DSLR) cameras and CCDs in their point-and-shoot compact cameras. The decision is partly based on the cost of the sensor and what sensors the companies want to market. The only way to tell which type of sensor is installed is by looking at the digital camera's specification sheet. There are cases where using one technology over the other makes sense. See Appendix K. Differences Between CCD and CMOS Sensors for advantages and disadvantages of the technologies.

The size of the sensor used is also dependent on the camera manufacturer. A full-size sensor is approximately the same size as the image area on 35mm film. The basic rule is: the larger the sensor, the better the image in terms of noise and dynamic range. Compact digital point-and-shoot cameras use small sensors due to: cost, physical size of the camera, and because purchasers of compact point-and-shoot digital cameras are satisfied with the image quality of the smaller sensors. Figure 2.10 provides examples of image sensor sizes.

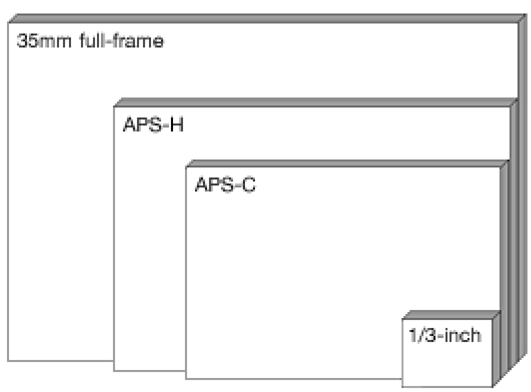

Figure 2.10 Sensor Image Size Comparison. Canon Camera Museum (2010)

Bayer Color Filter Array. In the mid-1970s, Bryce Bayer (Eastman Kodak) invented the Bayer Color Filter Array which enabled CCD and CMOS sensors to capture color images. Without the filter, a digital camera would require three separate image sensors (Practical Photography Tips, 2010). Most cameras made today use the Bayer Color Filter Array. The Bayer Color Filter Array shown in Figure 2.11 has blue and red filters at alternate pixel locations and green filters in the remaining locations. The pattern results in half the image resolution dedicated to accurate measurement in the green band (Maschal Jr., Young, Reynolds, Krapels, Fanning, & Corbin, 2010)

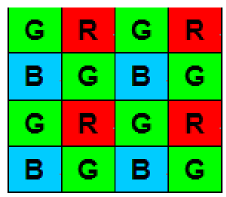

Figure 2.11 Bayer Color Filter Array

Infrared Cut Filter. Infrared (IR) is that part of the electromagnetic spectrum that lies just below visible light, just beyond what we can see. IR cut filters are used block IR light so that only visible light strikes the CCD and CMOS sensor. The result is an accurate color image. Figure 2.12 shows the relationship between the Color Filter Array, IR filter and image sensor in a digital camera (Photoaxe, 2011).

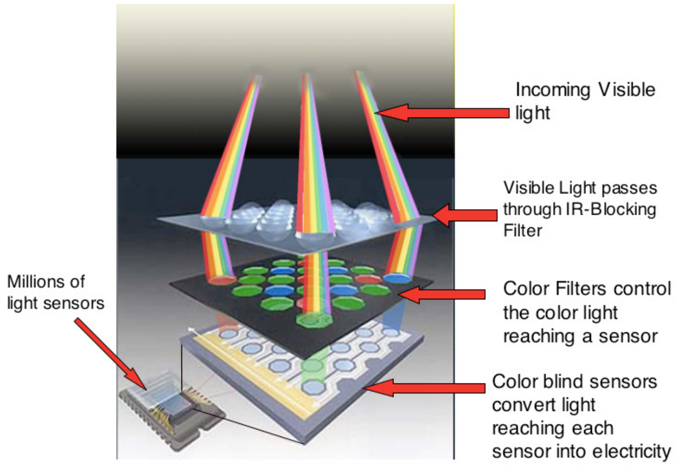

Figure 2.12 IR Filter, CFA, and Image Sensor Relationship

A simple test can be performed to determine if a digital camera has an IR cut filter. See Appendix M. Engineering Notes.

Lenses. The quality of the lens used in a digital camera depends on the cost of the camera and the focal length adjustment. Glass lenses are favored over plastic lenses. There are four basic types of lenses used in digital cameras and webcams (John, 2010):

- Fixed-focus, fixed-zoom lens – The most common. Used in inexpensive digital cameras.
- Optical-zoom with automatic focus. The user can adjust the focal length. Features include telephoto or wide options.
- Digital zoom.
- Replaceable lens. Digital cameras designed to mimic 35mm single reflex lens (SLR) cameras are designed this way. In many cases, the cameras will accept film camera lenses.

Crop-frame Sensors. Some low-end DSLRs come with "digital lenses'. A digital lens is a lens designed to be used with crop-frame sensors. Crop-frame sensors are smaller than 35mm film dimensions so the lenses designed for them project smaller circles of light. Figure 2.13 (Miller, 2008) is an image taken using a film SLR with a digital lens installed. The white square indicates the size sensor the lens was really designed for. (Teledyne Dalsa, 2011).

Figure 2.13 Example of Crop Factor Sensor Sizing.

Optical Zoom v Digital Zoom. Optical zoom is performed by physically moving the zoom lens so that it increases magnification of the image. Digital zoom is has nothing to do with the camera optics. The camera software expands a portion of the image and makes it look bigger on the computer monitor. Many digital cameras offer both types of zooming.

Shutter. The purpose of a shutter on a camera is two-fold: 1) the prevent light from hitting the film when you don't want it to, and 2) to make sure light hits the film when you want it to. Camera manufacturers spent decades figuring out how to make shutters faster and more accurate. Many small point-and-shoot digital cameras don't have shutters. Instead they use an "electronic shutter" (Miller, 2008).

An electronic shutter is kind of misleading. First of all, the digital image sensor is always exposed to light unless the lens cap is on or when the camera is turned off.

When an image is initiated, the camera electronics turn the sensor electronics on and then off again. That could be 1/60 of a second or 1/1000 of a second, depending on the selected (or preselected) exposure interval programmed into the camera. The term shutter speed is traditional so the terminology also applies to digital cameras. In Figure 2.14 the CMOS sensor in the camera is always exposed to light. An electronic shutter is used to control exposure (Davidson, 2003).

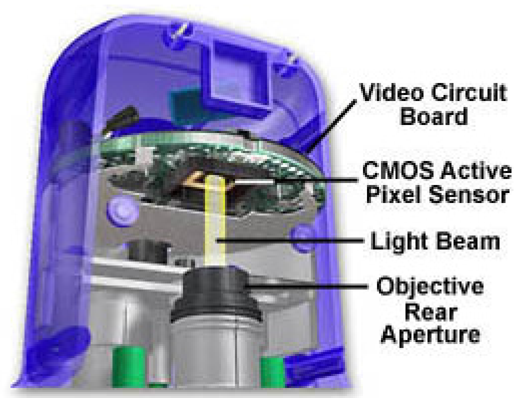

Figure 2.14 Example of a Shutter-Less Digital Camera

Electronic shutters or switchable digital light sensors are complicated “because in addition to all the individual light sensor pixel photosites, microlenses, electron storage wells, and circuitry to move the data from them to the camera's electronics, they need additional electronics to control the switching.” (Miller, 2008) There is some trade-offs in image quality such as:

- The camera manufacturer must limit the area of the sensor that is actually used.
- The sensor may not perform as well in low light situations due to fewer photons being captured.
- The images may have more noise in them.

Another type of electronic shutter is a “rolling shutter” which ‘paints’ the image on the sensor from top to bottom. There are also hybrid shutters that use a combination that use a mechanical curtain and switchable sensors used on some low-priced DSLRs. (Miller, 2008)

Some small point-and-shoot cameras use another type of electronic shutter called an “interline transfer sensor”. The interline transfer sensor sets aside a portion or each pixel to store the charge for that pixel, but storing the charge for each pixel also reduces the fill factor, which reduces its ability to capture light. Interline transfer sensors have higher noise levels and lower sensitivity, but this design eliminates the need for a mechanical shutter thus reducing the size of the camera to easily fit in a shirt pocket (Chaney, 2011).

Illumination. According to Microscan (2011), a leader in machine vision lighting equipment, “90% of the success of any machine vision application is through proper lighting. If the camera can’t see it, it can’t be read or measured.” Most lighting is selected by its brightness and spectral quality, but cost, flexibility, longevity, maintenance and stability are also considered important factors. Frequently more than one type of lighting is used to attain the desired effect. Most experts agree that the there isn’t one type of lighting that can do everything (National Instrument, 2008).

The final illumination techniques selected for this project are detailed in Appendix H. Lighting System Analysis and Design.

Filters. Filters are one of the least expensive ways to change how an image looks. This was especially true with film photography. With digital photography, photo-editing software has reduced the need for many filters, but they are still used for effects. For machine vision filters are used the same way. The most common filters used with machine vision are the same ones used in photography and for the same reasons: to eliminate unwanted reflection or to accentuate specific features. Ultraviolet (UV), infrared (IR), fluorescence, neutral density, polarizers, and colored lenses are used.

Illumination Effects: Specular and Diffuse Reflections. Specular reflection (also known as direct reflection or glare) is reflection generated in one direction. It is bright, but unreliable. It is unreliable because a small change in the angle between the light source and the object may cause the specular reflection to disappear. In other words, if very precise positioning is not position, do not depend on specular reflections. In diffuse reflection, incoming rays are scattered over a range of outgoing angles so the result is “dim and stable”. The large solid angle of reflection allows the image to be almost constant as the angle changes. Figure 2.15 shows the difference between specular and diffuse reflections (CVI Melles Griot, 2009) (Hunter, Biver, & Fuqua, 2007)

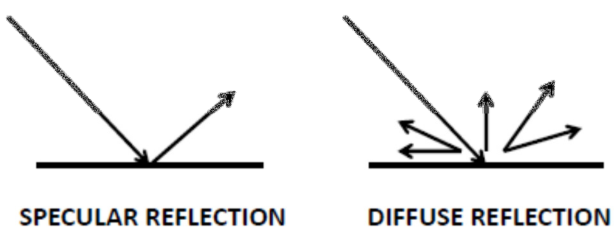

Figure 2.15 Reflection Types

Illumination Techniques. Simple lighting techniques can overcome problems with reflections: point-like lighting and diffuse lighting. Point-like lighting is easy to design because it uses small illuminators that can be placed away from the object. Examples of Point-like illuminators are: optical fiber bundles, incandescent lamps, ring lights, and LEDs. All of these produce point-like illumination that create sharp edges, shadows, and accent surface finishes. Diffuse lighting is used to reduce shadows and reduce glare. The trade-off is that diffuse lighting can blur image. Diffuse lighting is also much more difficult and complex than point-like illumination. Diffuse lighting requires that the lens, camera, and stand be mounted around the illuminator (CVI Melles Griot, 2009). See Appendix H. Lighting System Analysis and Design for additional information.

Contrast. Contrast is defined as being the measurement of separation between the light and dark areas in an image where there is a change in brightness from one point to another. An image of the highest contrast is one where the black is really black and white is really white without any shades in between (Edmunds Optics, 2011). Figure 2.16 is an example of high contrast.

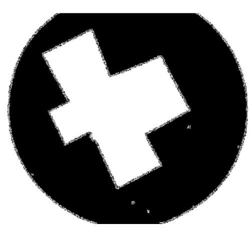

Figure 2.16 Example of a High Contrast Image

Light Emitting Diodes. Lighting using Light Emitting Diodes (LED) have become popular due to their design flexibility, stability, longevity, intensity, and cost-effectiveness. Since their introduction in the early 1960s, the use of LEDs has spread from simple indicator lights to more advanced forms such as task lighting and automotive tail lights. LEDs are radically different from traditional forms of lighting in appearance and how they operate. LEDs produce light by applying an electrical current to a chemical chip embedded in a clear plastic capsule. The color the LED produces depends on the chemical composition of the chip (Illuminating Engineering Society, 2011). Figure 2.17 shows a cutaway of an LED and its various parts (Slices of Life, 2011).

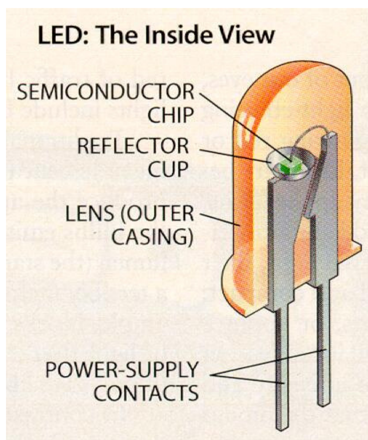

Figure 2.17 LED Cut-Away

LED illuminators have several advantages over traditional illumination sources. They are flexible, long-lasting, fast, shock resistant, low heat, and are available in a large range of colors. Fixtures can be easy to make (CCS, 2011). In this project, LED ring lights were selected for microscope illumination.

DIGITAL IMAGING SOFTWARE TOPICS

In this section digital imaging software, how lenses can affect image outcome, edge detection algorithms, and computer aided drafting software. The final software selection is detailed in Appendix F Software Analysis.

Digital Image Processing for 2D Vision-based measurement. There are four steps in the digital image processing necessary to convert a digital image into a CAD file: (1) scanning, (2) storing, (3) image enhancement, and (4) conversion from raster to vector graphics. Understanding each of these processes in a little more detail makes it easier to determine the best approach to use.

Scanning. All digital cameras use scanning hardware and software to generate images. Scanning is performed using CCD or CMOS sensors along with software supplied by the camera manufacturer.

Storage. Depending on the digital camera, the image may be stored locally in memory until it is downloaded to a computer for other digital imaging processes or directly to the host computer if the digital camera does not have image storage capability. Digital cameras may come with image generating software which, among other things, determines how the digital image will be saved and if lens distortion, image contrast, or color correction is required.

Image Enhancement Software. The amount of software available on the market to modify or enhance digital images available today is enormous. Selecting the appropriate image enhancement software depends on a number of factors including the operator’s level of experience and the cost of the software.

Aspect Ratio, Image Resizing and Cropping. An aspect ratio is the ratio of the width and height of an image. The aspect ratios for digital images are mathematically expressed as a grid using a count of the image sensor pixels in the horizontal and vertical directions. For clarity, an aspect ratio is usually stated as a ratio of the horizontal to vertical dimensions as “x-to-y”. For example, a 1280x960 pixel image is said to have an aspect ratio of 4:3 (4 to 3).

Resizing or resampling a digital image using software maintains the aspect ratio, but changes the pixel resolution.

Cropping is used to resize images. Traditionally, cropping was used to trim paintings, prints, and photographs to fit a specific location such as a smaller picture frame. For digital images, cropping not only reduces the size of the image, the number of pixels, and the aspect ratio, but it does not change the image resolution. The primary purpose is to improve the image composition (i,e, remove unwanted detail).

In this thesis project, images may be cropped if generated on a flatbed scanner, but never resized.

Image Contrast. 2D vision-based measurement requires sharp, high contrast silhouettes. Good silhouetting can be accomplished using the proper illumination and filtering, but sometimes additional contrasting using image enhancement software is necessary.

For example, in Figure 2.19, the histogram shows the dark gray levels are tightly packed together at the left end and the bright pixels are tightly packed at the right end. The image has high contrast and is a good candidate for raster to vector conversion.

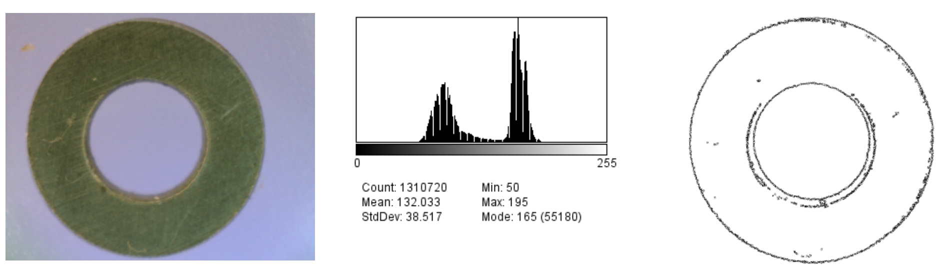

Figure 2.18 Histogram Example 1

In Figure 2.20, the histogram shows the gray levels are spread out and the image is well contrasted. This image is a poor candidate for raster to vector conversion.

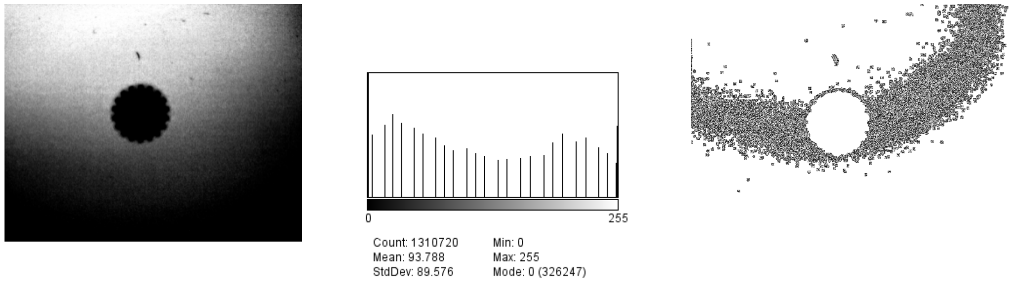

Figure 2.19 Histogram Example 2

Analyzing a histogram is straight forward, but using examples makes it easier. See Appendix J. Image Analysis and Histogram Study for more details.

Lens Distortion, Focus, Magnification, Resolution, and Dynamic Range. In this section lens distortion, focus, magnification, resolution, and dynamic range and their effects relative to digital imaging are examined. The information presented here is high level and used as an introduction**.**

Lens Distortion. Lens distortion is an optical aberration caused by how a lens projects light rays over a flat sensor or film surface. This distortion does not depend on the focal length of the lens though is more obvious on wide angle and mega-zoom lenses (DXO Image Science, 2011). Distortion is a property of lens design and not the result of manufacturing errors. Lens distortion issues are often small enough to ignore because they can be removed by software that is built into the camera or when post processing the image (CVI Melles Griot, 2011).

With a perfect lens all straight lines would be straight regardless of where they happen to be in the image. Real-world lenses are not perfect and are commonly affected by barrel or pincushion distortion; see Figure 2.14 (DXO Image Science, 2011).

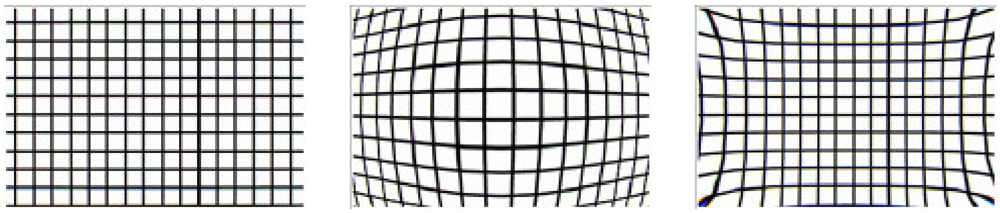

Figure 2.20 Examples of Lens Distortion

Barrel distortion or fish-eye effect is caused by the center of the lens being closer (convex) to the object than the outer edges of the lens. In pincushion distortion the center of the lens is further (concave) from the object than the out edges of lens. Mustache or complex distortion is a combination of the two (Gear Oracle, 2011).

There are several methods for correcting lens distortion. The first way is to use a better camera, but that is not always possible. Digital camera manufacturers sometimes include built-in software to compensate for lens aberrations after the image is scanned, but before it is downloaded to the personal computer. By making the compensations in the software, manufacturers can spend less on optical design, thus keeping the costs and camera size down. In some cases manufacturers include customized proprietary digital image processing software with their cameras or rely on third party software like Adobe Lightroom and Photoshop (Gear Oracle, 2011).

Focus. Photography is all about deciding what to emphasize in the image and what is not important. In digital microscopy, manual focus is almost always preferred because of the size of the object being photographed and because auto-focusing may focus on the wrong part of the object or not on the object at ***all.***

In macrophotography and digital microscopy blurry images can be caused by poor focus, subject movement, distance of subject to lens, camera shake, and wind. Solutions: Operator corrected vision, rigid camera mounting, proper camera alignment with subject, eliminate or reduce reflective surfaces that cause noise or spots, and a lot of practice.

Magnification. Magnification is how much an image is enlarged. With an optical microscope, magnification is found by multiplying the eyepiece magnification by the lens magnification. Because USB microscopes lack eye pieces the magnification is determined by how many times larger the object appears on the computer monitor. Magnification is also dependent on the sensor size (CVI Melles Griot, 2011, p. 10).

While the magnification of a traditional light microscope can be easily determined, the USB microscope is a video camera with a macro lens. Knowing precisely what the magnification is for images produced by the USB microscope has no effect on the outcome for this project. .

Resolution. Resolution is defined as the amount of detail that can be seen in an image. For digital images, the following rules are used to define the resolution (Microbus, 2007)***:***

- A digital image is defined as the number of pixels in the image or the pixel length x width. For example: a 1280x1024 pixel image is a 1.3 Megapixel image. A 2048X1536 is a 3.1 Megapixel image. A 3.1 Megapixel camera can produce a larger image than a 1.3 Megapixel camera.
- How much of an image can be seen on the computer monitor is dependent on how it is set. If the monitor is set to 1280 x 1024 pixels, a 640x480 image will only take up a portion of the screen.

Wikipedia (2011) provides an excellent example comparing pixels and resolution. In Figure 2.22, each square is the same size, only the number of pixels changes. The image becomes more detailed as the number of pixels increases and the resolution improves.

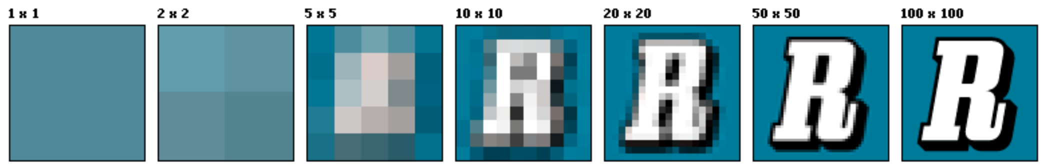

Figure 2.21 Image Resolution Example.

Sensor Resolution and Efficiency. The resolution of an image sensor is a function of the number of photodiodes and their size relative to the image projected on the surface by the camera or microscope optical system (Parry-Hill, Griffin, Davidson, & Vogt, 2010). The efficiency of capturing images is dependent everything from external illumination, camera quality, image sensor photodiode array size, to how the proprietary software manipulates the image.

Sensor efficiency is dependent on factors ranging from the "objective magnification, numerical aperture, and resolution, to the electronic image sensor photodiode array size, aspect ratio, video coupler magnification, and the dimensions of individual photo-sensitive elements within the array." (Parry-Hill, Griffin, Davidson, & Vogt, 2010) Parameters specific to the object being imaged such as "contrast, signal-to-noise ratio, intrascene dynamic range, and integration time" should also be considered (Parry-Hill, Griffin, Davidson, & Vogt, 2010).

Optical versus Interpolated Resolution. Optical resolution, also called native resolution, is the number of pixels in the image sensor. The number of pixels determines how sharp and clear the image is. Interpolated resolution artificially creates extra pixels by matching the color of the surrounding pixels automatically. An interpolated resolution creates an artificial image, which, may not be a problem depending on the application.

Edge Detection. Edges contain some of the most useful information in an image. Edges are used for measurement, to isolate particular features from their background, and to recognize and classify objects. Edge detection algorithms are used to find pixels in areas of high contrast in gray scale images. These areas are likely to be where an object ends and where the background begins (Intelligent Perception, 2010). More precisely, these are the areas where the change of the gray – from light to dark or dark to light – is the fastest. A threshold value is needed so that all pixels where this change is higher are considered "edges." The following algorithms are examined in this section: Canny and Sobel.

Canny Edge Detection Algorithm. The Canny Edge Detection algorithm, developed by John Canny (1986), is considered by many to be the optimal edge detector. It was designed to meet three criteria for edge detection. (McAndrew, 2003) (Green, 2002):

- Low error rate of detection. It should find all the edges and nothing but the edges.
- Localization of edges. The distance between actual edges in the image and edges found by the algorithm should be minimized.
- Single response. The algorithm should not return multiple edge pixels when only single edge pixels exist.

Based on these criteria, the Canny Edge Detector algorithm is as follows (Green, 2002):

1. Smooth image to eliminate noise and to detect edges.
2. Locate the image gradient to highlight regions with high spatial derivatives.
3. Track along these regions and suppress any pixel that is at non-maximum suppression.
4. The gradient array is now further reduced by hysteresis. Hysteresis is used to track along the remaining pixels that have not been suppressed. Hysteresis uses two thresholds, a low-value and a high value:
    a. If the magnitude is below the low threshold, it is set to zero (made a non-edge).

b. If the magnitude is above the high threshold, it is made an edge.

c. If the magnitude is between the 2 thresholds, then it is set to zero unless there is a path from this pixel to a pixel with a gradient above high threshold.

In comparison to other edge detection algorithms (ie, Prewitt, Sobel, etc.) the Canny Algorithm produces a substantially cleaner image. Its parameters allow it to be tailored to recognize a variety of different edge characteristics. Performance-wise, might be a little slow for real-time image processing, but that is dependent on available computing power.

In Figure 2.23 (right) the Canny Edge Detection algorithm is applied, but in reverse image to make it easier to read. A Matlab script was used to apply the Canny Edge Detection Algorithm to image in Figure 2.23 (left). See Appendix M. Engineering Notes.

Figure 2.22 Result from Applying the Canny Edge Detection Algorithm (Intelligent Perception, 2010)

Sobel Edge Detection Algorithm. The Sobel Edge Detection Algorithm acts locally on the image and only detects edges at small scale. If an object with a jagged edge is present, it will find the edges at each “spike and twist.” The algorithm is sensitive to high frequency noise (disturbances in light, color, or density in the image) and will generate only local edge data instead of the entire boundary structure. In contrast, smooth transitions that occur over too large a spatial scale to fit in the 3x3 window of the Sobel operator will not be detected (Jebara, 2000).

In Figure 2.24 (right) the Sobel Edge Detection algorithm is applied, but in reverse image to make it easier to read. A Matlab script was used to apply the Sobel Edge Detection Algorithm to image in Figure 2.24 (left). See Appendix M. Engineering Notes

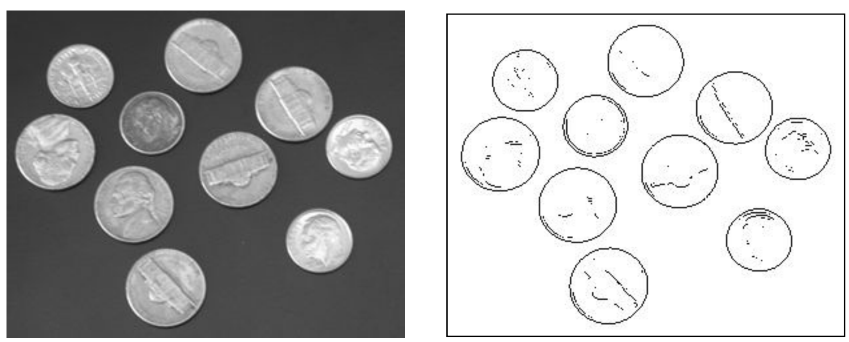

Figure 2.23 Result From Applying the Sobel Edge Detection to an Image of Coins (Intelligent Perception, 2010)

Binary Conversion. In a binary image, each pixel is either black or white (1s and 0s). In this project, binary conversion may take place before or after edge detection algorithms are applied. The process is simple (McAndrew, 2004, p. 217):

Step 1: Convert image to grayscale.

Step 2: Select a grayscale threshold level (T).

Step 3: pixel is White if its gray level is $> T$.
Black if its gray level is $\leq T$.

Thinning Methods: Zhang-Suen and Stentiford. Thinning or skeletonization is applied after the image is converted into a binary file and edge detection has been applied. Digital image thinning methods are used to convert a dense pixel image into thin image. Figure 2.25 shows a before and after example of using a thinning algorithm to reduce the image to its most basic form.

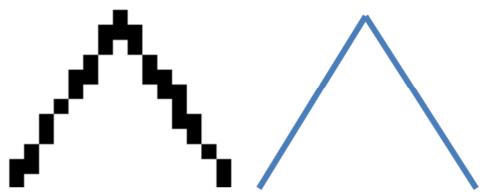

Figure 2.24 Thinning Example

A variety of thinning algorithms may be used to convert a raster image to vector. In this project the goal is to produce an outline of the object being inspected. Stentiford, and Zhang-Suen thinning algorithms were chosen for this project.

The Stentiford (Figure 2.26, right) thinning methods works well on lines that follow curves and is extremely accurate in following shapes. The Zhang-Suen (Figure 2.26, left) thinning method is better at extracting straight lines, so it is better when working with angular outlines (Soft Soft, 2011).

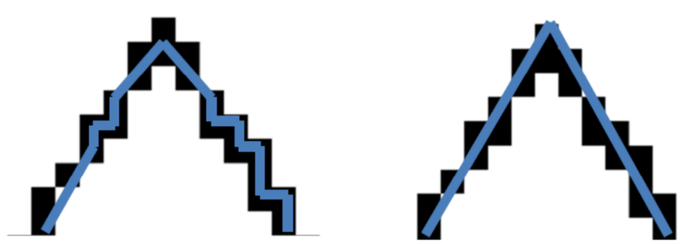

Figure 2.25 Thinning Algorithm Examples
Left: Zhang-Suen, Right: Stentiford

Noise. According to Alisdair McAndrew (2004, pp. 188-191), noise, also called speckling or salt-and-pepper, is degradation in the image signal caused by an external disturbance. If we know what kind of noise to expect, we can select the best method for reducing its affects. For this project, the speckling or noise in a digital image is mainly created by lighting and the types of surfaces included in the digital image. Examples include: bright lights, coarse, shiny surfaces; and color. The best practice is to set up the image without any of these distractions, but that is not always possible. Figure 2.27 has two examples of images with large amounts of speckling.

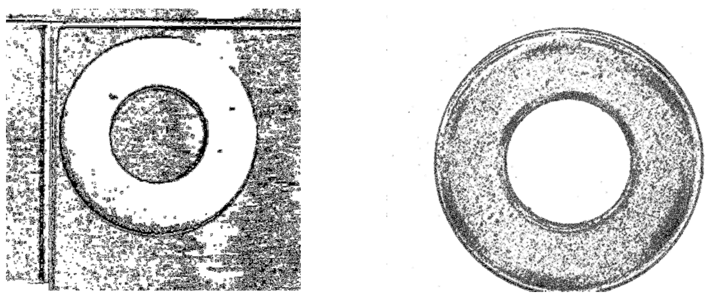

Figure 2.26 Examples of Speckling

The speckling in Figure 2.27 (left) was caused by direct bright light on a brushed metal surface. Not only does speckling increase the image size, but it also can obliterate the edges of the object being examined making it more difficult to measure. Figure 2.27 (right) is an image of the same washer generated using a piece of paper for the background. While specking still occurs due to the shininess of the washer's surface, its outline is very distinct. This image would be a better choice for CAD conversion.

Some digital image processing software applications include filtering processes that may remove or lessen the amount of speckling. Unfortunately, despeckling is a manual process and the object outline may be difficult to find. See Figure 2.28.

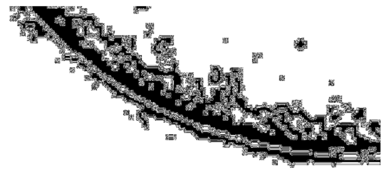

Figure.2.27 Detail of a Speckled Outline

Raster to Vector. Most raster to vector algorithms are proprietary, but there are a few open source examples available. The most common vector graphics file format is the Design Exchange Format (DXF) developed by Autodesk in the early 1980s. The DXF format is accepted and widely used in the CAD industry and is supported by most programs.

Converting a raster image to vector graphics is essentially a matter of connecting the dots. Two methods were researched for converting raster images into vector graphics.

The first is manually tracing the raster images. Manual tracing is a very tedious method for converting a raster image into vector graphics. Basic instructions for how to do this can be found on various websites on the internet. The following procedure is fairly common for manual tracing:

1. Open the vector program. Adobe Illustrator is an example of a vector-based program.
2. Paste a copy of the raster image in the program's working window.
3. Resize the graphic to the size as needed.
4. Trace the raster graphic using vector-based commands directly on top of the image.
5. Delete the raster image.
6. Save the new vector graphics.

The second method is to use software specifically designed for converting raster image to vector graphics. There are many excellent programs that can perform this task.

Computer Aided Design. “Computer aided design”, according to John Walker **(2011)**, founder of Autodesk, Inc. and co-author of AutoCAD, “is the modeling of physical systems on computers, allowing both interactive and automatic analysis of design variants, and the expression of designs in a form suitable for manufacturing.”

Today anyone with even the smallest knowledge of computing has heard about Computer Aided Design (CAD). CAD started appearing in engineering offices in 1969 in the form of complete computer systems kluged together using minicomputers such as the Data General Nova 1200 and DEC PDP-11s using Tektronix storage tube for displays. These systems included digitizer tables, specialized keyboards, and sometimes tablets for coordinate entry. System hardware included a 16-bit minicomputer with a 10-20 MB hard drive and up to four terminals. Other equipment included ink and pen plotters by Calcomp, Xynetics, and photo plotters by Gerber (Weisberg, 2011).

By the 1980s, the architecture of CAD systems started moving toward standalone engineering workstations. The engineering workstation was a high-end stand-alone computer designed for companies needing faster microprocessors, large amounts of RAM, and special features such as high-speed graphics adapters. In the 1980s, most engineering workstations were physically connected (hardwired) to a mainframe or mini-computer computer.

The personal computer industry exploded in the 1970s, but software took several years to catch up as people began figuring out what to do with it. In 1983 Autodesk, a small software development company, began delivering their product, AutoCad, a CAD software designed to run on personal computers with high performance microprocessors and math-coprocessors made by Intel and third party graphics accelerator cards.

Design Exchange Format. The Design Exchange Format (DXF) was developed by AutoDesk in 1982 as a universal format for vector image files so that AutoCAD documents could be opened more easily with other programs (The File Extensions Resource, 2011) (CoolUtils, 2011). It is supported by large number of programs including AutoCad, TurboCAD, DWG2Image Converter, and PowerCAD.

Some third-party CAD programs are inconsistent in converting CAD drawings to DXF format. Inversely, not all third-party CAD programs can consistently interpret DXF files. Some of the software tested for this project had trouble opening DXF formatted files generated by other software.

CASE STUDIES

The following five case studies were selected for this research. Information learned from each of these case studies was applied to this thesis project.

- The Tormach CNC Scanner, utilizes a USB microscope and CNC control software to measure parts.
- University researchers experimented with a common office flatbed scanner to measure fine electrical wires.
- A Nikon vision system: an example of what most customers would expect in a vision-based measurement tool.
- Applying photogrammetric principles to macrophotography.
- A simple raster image measuring software.

Case Study 1 – Tormach CNC Scanner. In 2010, Tormach LLC, a manufacturer of small personal CNC mills, developed a 2D scan tool called the Tormach CNC Scanner. The CNC Scanner uses a manually focused USB microscope with a proprietary holder that can be mounted on the spindle of any CNC mill that utilizes the ArtSoft PC-based Mach 3® motion control software.

The CNC Scanner software, a Mach 3® plug-in, is used to determine the "exact position and number of photographs taken depend on the desired size and resolution of the photomosaic", then generates a stitched image of the object. After the stitched image is assembled, it can be opened in Tormach CNC Scan CAD®, a simple 2D CAD program with basic functionality for measuring distances and tracing shapes. This information can be exported as an industry standard DXF file to other CAD/CAM programs for further work.

Two methods for measurement can be used with the CNC Scanner : A scale placed in the image, or using "the controlled motion of the mill itself to establish scale by calibrating the change of position in a particular point in the field of view to the actual distance that the mill traveled." According to Tormach, the CNC Scanner is capable of ±.001 inch accuracy.

Case Study 2 - Measuring Fine Wire using a 2D Flatbed Scanner. In 2009, C. W. Kee and M. M. Ratnam of the Universiti Sains Malaysia learned that handling fine wires and measuring them using manual metrology tools such as digital calipers, micrometers, microscope, optical comparators can be difficult. One of their experiments was to use a high resolution office flatbed scanner, a PC, and Matlab software to measure the wires instead.

Nine wire samples were selected for the experiment and were measured using an optical comparator. Then the samples were scanned on an office flatbed scanner at 1200, 2400, and 3600 DPI. A 10mm gage block was used to determine the scaling factor for the scans. Canny, Sobel, Laplacian, Roberts, and Prewitt edge detection algorithms were applied to the scan results as well as a scaling algorithm using Matlab scripts.

The results of their experiment showed that they were able to achieve an accuracy of 4.5% measuring the wires with a low cost office flatbed scanner. In their conclusion Kee and Ratnam (2009) noted that "compared with the usual method of measuring wire diameters using a micrometer, the proposed technique is fast, accurate and reliable. Since the wire is scanned after closing the scanner cover the measurement results are relatively unaffected by environmental conditions, particularly ambient lighting."

Case Study 3 – Nikon VMA-2520 iNEXIV Multi-sensor Measuring System. The Nikon iNEXIV VMA-2520 is a multi-sensor measuring system that is lightweight and compact enough to be used in the factory on the bench top, with fast, fully automatic and high accuracy features that make it ideally suited for a wide variety of industrial measuring, inspection and quality control applications such as cracks, material failure, and surface analysis, manufacturing inspection processes, and metallurgy.

Compared with measuring systems described in the other case studies, the Nikon vision system is a "Jack-of-all-trades". The system has three different measuring methods that can be combined to provide "greater measurement capability, avoids the need to examine samples in multiple steps, and greatly increases the inspection efficiency." These include: "video for edge detection, lasers for measuring surface features, and a touch probe for measuring "'hidden' areas inaccessible to video or laser techniques." Nikon's proprietary AutoMeasure software provides excellent control over the system and can be upgraded with various modules to expand the capability of the system. Additional software modules include: Gear analysis, 3D surface analysis, 3D graphics generation, real time SPC reporting, and automated report generation. (Nikon Metrology, 2011)

Case Study 4 – Applying Photogrammetry Principles to Macrophotography. The following case study is included for its historical significance in the area of micro-photogrammetry.

In 1999, Mitchell, Kniest, and Won-Jin presented a report on applying commercial digital photogrammetry principles to photographs generated via stereo microscope. In their research they found that applying photogrammetric methods to microscopes was difficult because microscope used had a very narrow field of view, the depth of field was very shallow, and "there are obvious photographic configuration restrictions." They discovered with digital imaging that there was a need for control points due to "unusual image scales, the uncommon pixel sizes and the unconventional and uncertain imaging geometry.” Though their study was limited, the authors concluded that microscope photogrammetry has special difficulties, but digital imaging software could easily cope with these problems.

Case Study 5 – NASA’s AnalyzingDigitalImages Software. The AnalyzingDigitalImages software was created by John Pickle and Jacqueline Kirtley of the Museum of Science in Boston, Massachusetts, with NASA funding. Originally the software was devised for the Global Systems Science student series for the Lawrence Hall of Science. Later on it was revised to support the NASA funded project: Digital Earth Watch, originally named Measuring Vegetation Health.

The AnalyzingDigitalImages software, freeware offered by the University of New Hampshire’s Measuring Vegetation Health program, has the user include a reference in the image as a control marker in order to calibrate the image using a known measurement. In Figure 2.29 a ruler is used to measure a leaf. Any object with a known dimension can be used (Managing Vegetation Health, 2008). The algorithm used by this software converts pixels to inches or mm by using the user’s reference measurement for input. The AnalyzingDigitalImages software is freeware, but is not currently supported.

Figure 2.28 Example of Target Reference Using the Analyzingdigitalimages Software (Managing Vegetation Health, 2008)

3. 2DNCMT SYSTEM DESIGN

Commercial two-dimensional vision-based measurement systems come in a variety of proprietary designs and most come with proprietary software as well. Manufacturers of machine vision systems are highly competitive and, as a consequence, most are reluctant to provide much information about the machine design and software processes they use. The Case Studies in Chapter Two were used as guidelines for developing the 2DNCMT for this thesis. The primary goal for the 2DNCMT hardware design was to generate high contrast silhouettes or high contrast, low shadow images of the objects being examined.

Table 3.1 outlines the contents of this chapter and the research performed in order to design and build the 2DNCMT.

Table 3.1

Chapter 3 Outline

Section	Title	Description
3.1	Project Requirements	This section lists the high level project requirements.
3.2	Project Budget	Project budget for the 2DNCMT.
3.3	Contrast	A definition of contrast and methods to achieve the appropriate image contrast for the 2DNCMT.
3.4	2DNCMT Hardware	Research for the 2DNCMT hardware is described in this section. This includes the stage, microscope mount and frame.
3.5	Illumination	Research for upper and lower illumination, and methods for resolving imaging issues such as stray light, shadowing, contrast, and noise.
3.6	Software Selection Criteria and Project Requirements	This section discusses the limitations imposed on software selection for this project. In order to keep the project under budget any software selected must be free or low cost. This section also describes the types of software needed for the project.
3.6	Image Calibration and Scaling	This section describes the research of the techniques used for calibrating and scaling digital images.

PROJECT REQUIREMENTS

- Low cost. Under $500US. In order to make this tool attractive to individuals who would not normally be able to afford this type of technology.
- All software used is open source or freeware. Software selected must be actively supported and readily available to anyone.
- All hardware is to be purchased from a local hardware store, computer store, or internet sales.
- All parts assembled or fabricated using basic hand tools, except where noted.
- All materials used for fabricating custom parts are available from local stores with an eye on assuring minimal waste. No student discounts for materials.

PROJECT BUDGET

No more than $500US including the cost of experiments and mistakes.

CONTRAST

In film and digital photography, the definition of contrast is the difference between brightness and color of the objects in the image. For the 2DNCMT, digital images must have high contrast so that the edges of the object being examined can be converted into lines no more than one pixel-width wide with minimal noise.

There are three methods for generating contrast:

- Mechanical methods such as using color, IR, UV, or polarizing filters, blocking or diffusing light from striking the object, and changing the aperture and shutter speed of the camera.
- Software can be used to modify the image.
- A combination of mechanical and software methods can be used.

What method used is dependent upon the physical attributes of the object being examined and the experience of the operator.

HARDWARE

The 2DNCMT is a simple machine made from consumer off-the-shelf parts and using fabrication methods that can be performed with household hand tools. This section is a record of the research performed for the hardware portion of this thesis. The final build is detailed in Appendix B. Machine Build.

The physical design of the 2DNCMT is based on a mixture of stereomicroscope and light microscope design as shown in Figure 3.1. Table 3.2 describes the hardware in more detail.

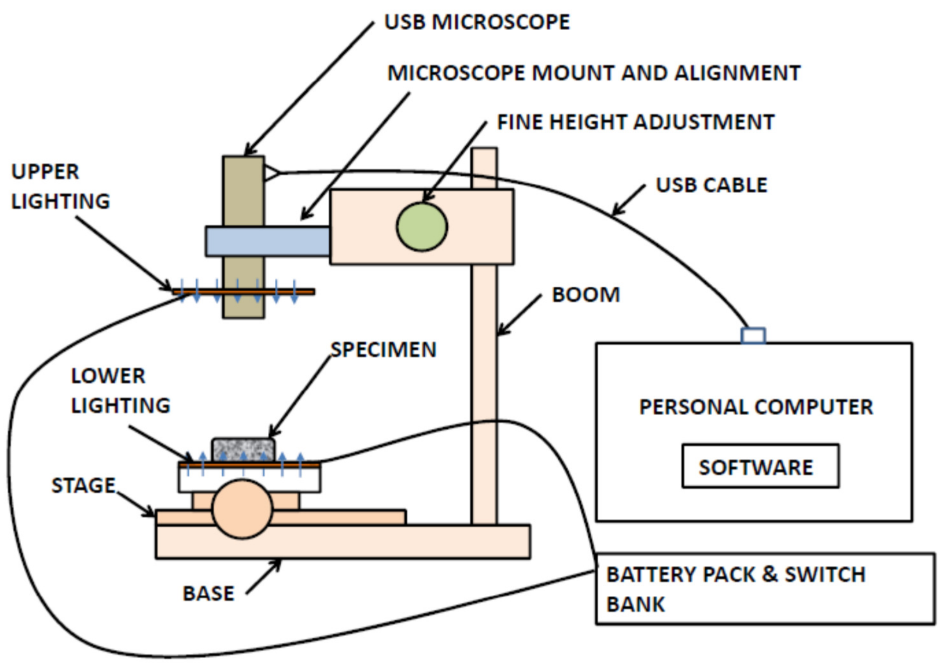

Figure 3.1 2DNCMT Schematic

Table 3.2

2DNCMT Hardware

Part	Description
Microscope Frame	The microscope frame consists of a base and boom. This frame was used to hold all the hard parts of the scan tool except the personal computer, battery pack, and switch bank.
Stage	The microscope's stage was a compound table. The compound table holds the light box (lower illumination), and the object being measured.
Lower Lighting	A light box was used to backlight parts for 2D measurement. Backlighting improves edge detection by sharpening the image and reducing shadows.
Upper Lighting	Custom upper lighting was used to provide indirect illumination that increases contrast and eliminates shadows.
USB Microscope and USB Cable	The USB microscope was the heart of this noncontact measurement tool. The USB microscope was a combination screw-barrel style microscope and a video camera with a CMOS sensor. The USB cable attached the USB microscope to the personal computer.
Microscope Mount and Alignment	The microscope mount and alignment was used to hold the USB microscope perpendicular to the light box for the best possible imaging. The mount was also used to align the microscope with the light box in the Y-axis.
Personal Computer	A personal computer was used to process the USB microscope images so that they could be viewed and measured in a 2D CAD system.
Battery Pack and Switch	The illumination was battery powered in order to make the 2DNCMT portable.

Microscope Frame. The physical design of the 2DNCMT is based on a mixture of stereomicroscope and light microscope design. That is, the USB microscope is mounted on a boom-style frame that is characteristic of stereo microscopes. The frame has a stage and light box more commonly associated with light microscopes.

Microscope Mount. In order for the USB microscope to be successfully used in this project, it must be supported and held perpendicular to the stage. Illumination must be designed to provide optimal lighting to the image whether it be backlighting or indirect illumination for shadow and glare reduction. To do this, the following parts or methods must be designed and fabricated:

- A Support frame to allow the USB microscope to be held at the desired height above the object being measured.
- A method for assuring the USB microscope is perpendicular to the stage surface.
- Illumination for backlighting and indirect floodlighting in order to achieve the best quality image.

A complete description of the final design may be found in Appendix B. Machine Build

Stage. With traditional microscopes, the object to be examined is first mounted to a glass slide or some sort of fixture and then placed on a platform located beneath the lens body called a stage. The stage is either fixed or compound. Fixed stages require the user to look through the eyepiece and manually align the object to viewing field. Compound stages allow the user to move the stage by rotating micrometer screws mounted in the x and y axes. Because of the size of the parts being examined in this project a compound stage is preferred.

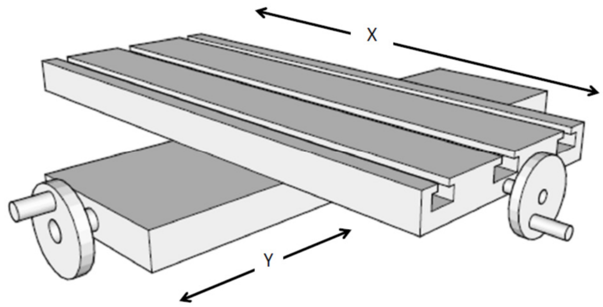

Figure 3.2 Compound Stage

Lower Illumination. A light box is used for lower illumination. The light box is a separate unit that is attached to the stage. It contains the lower illumination and a surface on which objects to be measured are placed. Research quickly revealed that a light box that would fit the 2DVMT design would be too expensive. A custom light box was designed instead. See Appendix C. Design Data for the final light box design.

Upper Illumination. There are many variations of ring lights for microscopes and cameras on the market that could be used, but none fit the project budget. An LED ring light was selected for the upper illumination, but a custom holder had to be designed and fabricated for it. The upper and lower illuminations are not used at the same time so the upper illumination must be able to increase contrast and at the same time, eliminate shadows. Appendix C. Design Data for the design and fabrication instructions for the upper illumination fixture.

Focusing Mechanism (Vertical Motion Control). One feature simple light microscopes have is the ability to raise and lower the optical assembly (eyepiece, optics tube, lenses) to bring the object being examined into focus. In order to do this, the vertical (z-axis) travel must be controlled. Three types of z-axis motion control were considered for this project:

- Traditional Rack and Pinion. A metal rack and pinion is used in better quality microscopes for focusing purposes and moving mechanical stages (Microscope.com, 2011). Most simple light microscopes use dual rack and pinion systems. One for coarse adjustment and one for finer adjustments. This design is the most complex, but the mechanism is easy to use and has a very short learning curve. No tools are required.

- Manual control. Manually moving the microscope mount in the z-axis and then fixing the position using some sort of clamping mechanism. Getting the microscope focused may be difficult. Manual control is a simple design, but the clamping feature may be difficult to use or require tools. There is chance that the microscope or other parts of the stand may be damaged if not careful.

- Manual control with fine adjustment. With this design, the microscope mount is moved up or down as a coarse measurement and then the clamp is secured. The fine adjustment, using a combination spring-lever-clamp design, allows the user to move the microscope up and down for focusing. The fine adjustment range of travel should be at least two inches.

The final vertical mount and motion control part selection and design are detailed in Appendix B. Machine Build.

Rotation. The vertical mount must also allow for 360-degree rotation of the microscope mount in order to accommodate parts that are too large to fit on the stage.

Power. The 2DNCMT was designed to be portable (battery operated) so that it can be set up and used in areas without power available nearby. Battery boxes, switches, and other electrical parts are readily available from electronics stores. A panel needed to be designed to hold the electrical parts securely. See Appendix B. Machine Build for the design and fabrication instructions for the power panel.

COLOR, IR, UV, AND POLARIZING FILTERS

Color, infrared (IR), ultraviolet (UV), and polarizing filters are used in digital photography to produce specific effects in images. In this project, the following filters were tested to determine if they could be used for contrast enhancement.

- Color filters: Yellow, Red, and Blue
- Ultraviolet blocking filter
- Infrared blocking filter: IR #750, #850
- Circular polarizing filter

Color Reflection. In commercial photography, using reflected colors can enhance specific features in images. In this project colored paper was used for reflection. Colors tested were white, yellow, black, and aluminum foil.

Aperture and Shutter Speed. The USB microscope used in this project does not have aperture or shutter speed controls that can be operated by the user. These mechanical techniques were not tested.

SOFTWARE SELECTION CRITERIA

Before discussing the actual software needed for this project, open source and freeware computer programs need to be briefly discussed. The purpose of this research is to develop and build a 2DNCMT for less than $500US. If this project were to use popular software such as Matlab, AutoCad, and Adobe Illustrator, the project would be instantly over-budget and the resulting measurement tool would no longer be a bargain.

Open Source. Open Source is defined as “software products that are freely available and offered by development communities online. They come with no warranty but are usually very well tested by development groups. “ (Glee Multimedia, 2011) Accessibility to the source code and development teams makes this type of software particularly attractive when developing a new application or technology. Open source software is not limited to hobbyists and students. Government agencies and companies contribute as well. A caution needs to be added here: Most open source software was developed for a specific purpose or customer so in many cases there isn't much interest in either supporting it or fixing bugs (Hormann, 2007). For this project, only open source software with an active support team was selected.

Freeware. Freeware may have a small fee attached, but in most cases, the author is not expecting payment for their work. Most freeware programs are small utilities, plug-ins, or incomplete programs. Sometimes the software is not open source, i.e. the actual code is not available, and the author retains the copyright (Indiana University, 2011). Only actively supported freeware was used in this project.

Project Software Requirements. This project had four different software processes to contend with: generate image, convert image to binary, and convert file from a raster image to vector graphics, and a 2D CAD software to scale and measure the vector file. While there might be a single software package capable of performing all of these functions that was not the case for any currently available open source or freeware application. See Appendix E. 2DNCMT Operating Procedure for final software selection and how the selected software was used.

The following three criteria were used in selecting the image enhancement software for this thesis project.

- Digital cameras are essentially computers. They have an operating system and a set of image enhancing algorithms that may or may not be controlled by the operator. The camera's software is used to compensate for lens aberrations and other features that would otherwise force the camera to cost more. Manufacturers of low-cost digital cameras and USB microscopes rarely provide details about camera software so one has to assume that the software installed in the camera is very limited.

- The choice of what format the camera manufacturer choses for storing images may affect the choices of enhancement software. Digital camera manufacturers usually provide this information along the maximum image resolution for the camera.

- What exactly is the software supposed to do? For the 2DNCMT described in this thesis project the enhancement software must generate a high contrast image from the original digital image generated by the USB microscope; apply the appropriate edge detection algorithm; convert the edge image to binary; and then convert the image using thinning algorithms to vector graphics.

Appendix F. Software Analysis contains the list of software that was researched for this project.

Digital Image Generation. Digital cameras are specialized computers designed to specifically to capture light and process it into digital images. Digital cameras come with embedded proprietary software routines that help compensate for less than perfect lenses, camera vibrations, low quality image sensors, image management, image processing, and how the image will be stored. Many cameras also come with additional software that is used to further process the image after they are downloaded to a personal computer, but before they are viewed and manipulated by the operator. Open source digital camera software is available, but most digital cameras are sold with proprietary software. In order to simplify this process, the software that came with the USB microscope was used for generating images.

Digital Image Processing. For this project digital image processing software that would convert the image generated by the USB into a binary raster file was needed. Open source software for is readily available. For this project, the digital image processing software needed to meet the following requirements:

- Read and save bitmap (BMP) images.
- Have edge detection capability to reduce images to simple outlines
.
- Capable of converting edge detected images to binary.

Raster to Vector Conversion. While some open source digital imaging processing software can convert a BMP file to DXF format, not all do the job well. During the research phase of this project, the following criteria considered for software selection:

- A raster to vector conversion application using Stentiford or Zhang-Suen skeletonization algorithms.
- Conversion from BMP to DXF format and maintain image sizing.

Two-Dimensional Computer Aided Drafting. Since Autodesk began selling their AutoCad® software in the early 1980s the number of other companies selling computer aided drafting software has exploded. There are plenty of well-respected companies producing open source and freeware CAD software. The following attributes are necessary for the 2D CAD software used in this project.

- Simple to use. The CAD software needed for this project does not need to be robust.
- Minimum commands: scaling, dimensioning, and simple drawing commands for lines, circles, and squares.
- Be able to save the results in DXF or DWG formats.

IMAGE CALIBRATION TECHNIQUES

Spatial calibration is the process for correlating the pixels in the image to 'real-world' measurement units such as inches, feet, or mm. There are three levels of spatial calibration used to correct various types of distortions in images (National Instruments, 2011). Simple calibration was the focus of this project, but the other levels need to be described for clarity.

1. Simple calibration has the camera perpendicular to the stage.

2. Perspective calibration corrects for lens effects when viewing the scene from an angle and applies a linear correction base on the geometry of the situation.

3. Nonlinear calibration is capable of correcting radial lens distortion as well as other effects such as local distortions from lens defects, atmospheric conditions, and irregular surfaces, etc.

Simple Calibration. Using a scale, grid, or reference target with a known dimension are methods used for accurately scaling 2D images in this project. Scales and grids are traditional methods for measuring objects under a microscope and have been carried over to digital imaging as shown in Figure 3.3. The use of reference targets with known dimensions is another method.

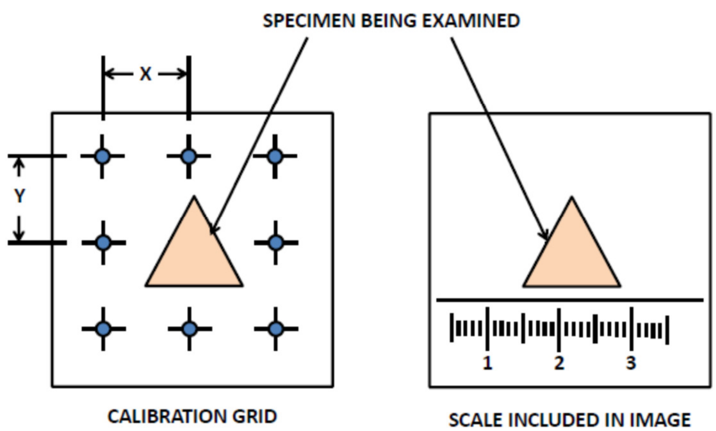

Figure 3.3 Traditional Image Calibration Methods Popular with Manual and Digital Microscopy

The use of a calibration grid or scale in the digital image works well for relatively flat specimens, but when the specimen has some thickness, accuracy may be lost because the grid or scale is on a different plane than the surface being measured. In order to fix this problem the reference target needs to be raised to the same plane as the object being measured as shown in Figure 3.4.

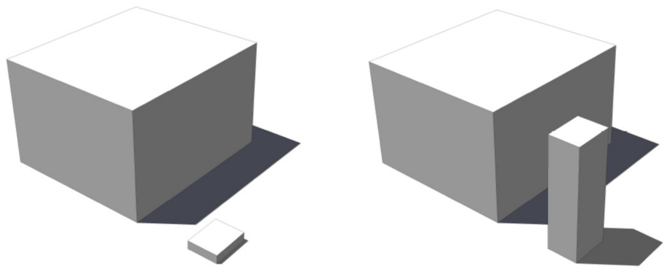

Figure 3.4 Dimensional Accuracy is Lost if the Reference Target is not on the Same Plane as the Object

Figure 3.4 (left) shows a discrepancy in height between the object and the reference target. Figure 3.4 (right) shows the reference target and object's surface at the same height. For more information about reference targets and target placement, see Appendix B. Machine Build and Appendix E. 2DNCMT Operating Procedure.

Scaling Images. After the image is generated and processed and converted into vector graphics (DXF formatted data), the grid, scale, or reference target placed in the image is used to scale it in the CAD environment. Vector images can be modified (scaled) more easily than raster graphics, because they contain descriptions of the shapes for easy rearrangement and they are also scalable at any resolution. It makes sense to convert the digital images into vectors and use CAD software for the final step.

Scaling Algorithms. The scaling algorithms used in this project were derived during the feasibility studies (see Appendix L. Feasibility Studies and Results) and were incorporated into the final 2DNCMT design.

Algorithm #1: Dual Scale Method. After several tests, the following algorithm was derived by modifying the simple percent reduction formula.

Percent Reduction Algorithm

$$New_{Value} = Old_{Value} – (Old_{Value} \text{ x } \%) \quad (1)$$

Algorithm Modified for Scaling

$$New_{Pixel} = |1/\{Old_{Pixel} – Old_{Pixel} \text{ x } ((Actual_{Dim} – Measured_{Dim}) / Actual_{Dim}) \}| \quad (2)$$

$$\text{Except if } Measured_{Dim} \neq 2 \text{ x } Actual_{Dim} \quad (3)$$

Analysis. This method was tested on several specimens with excellent results. Using this method for scaling parts does not change the scaling in the CAD environment making the CAD drawing incompatible with other CAD/CAM software.

Algorithm #2: Simple Scale Method. Most CAD software is capable of scaling images to any size. AutoCad has this capability as so other 2D CAD applications. The process is simple and straightforward:

1. Rescale image in CAD so that it is a 1 x 0.8 inch rectangle by using the horizontal pixel value.
2. Measure the reference target.
3. Divide the known reference target dimension by the measurement found in Step 2.
4. Rescale the image to the new value.

Analysis. This method was tested on several specimens with excellent results. Using this method for scaling parts changes the scaling in the CAD environment making the CAD drawing compatible with other CAD/CAM software***.***

4. TEST METHODS

This chapter outlines the feasibility studies, imaging techniques, equipment design, and the gage qualification process which includes a process capability and Gage R&R studies to determine the accuracy, precision, repeatability and reproducibility of the 2DNCMT. Table 4.1 contains the chapter outline.

Table 4.1

Chapter 4 Outline

Section	Title	Description
4.1	Feasibility Studies	Pre-project feasibility studies and results.
4.2	2DNCMT Equipment Tests	How to use the measurement tools.
4.3	Measurement Tests	Sample parts used in the test phase.

FEASIBILITY STUDIES

Two early feasibility studies are described in Appendix L. Feasibility Studies and Results.

2DNCMT EQUIPMENT TESTS

2DNCMT tests consisted of testing filters, colors, edge detection algorithms, and illumination techniques in order to determine how to achieve the best contrast. These tests were performed early in the research and completed before the measurement tests.

2DNCMT Equipment Tests. The following equipment tests were performed.

- Color IR and UV Filters
- Color Reflection
- Edge Detection Algorithms
- Illumination

MEASUREMENT TESTS

Nikon VMA-2520 - 2DNCMT Comparison Test. The first test performed was to compare the repeatability and reproducibility of the Nikon VMA-2520 and 2DNCMT systems. An AIAG Gage R&R study was performed on both systems using the same parts and the same measuring methods.

Several tests were run to determine the accuracy of the Nikon vision measurement system. Since the 2DNCMT is a manual measuring system, a similar method was used for measuring on the Nikon. On the Nikon, the Square function was used. In order to get the best measurement at least 4 points were needed. Those points were selected in specific areas, were considered random. Figure 4.1 shows how the measurement points were selected. On the Nikon, the silhouette of the part is displayed on the monitor and a pointer (mouse) is used to select points on the edge of the silhouette. Nikon's AutoMeasure software finds the exact edge and identifies the coordinate location of the point. At least four points are taken to determine the length and width of the rectangular shape. The software automatically calculates the distances and this data was exported to an MS-Excel spreadsheet.

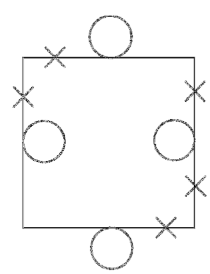

Figure 4.1 Point Selection for Measuring the Plastic Part using the Nikon VMA-2520

On the 2DNCMT, the images are opened in the 2D CAD application, scaled to the proper size, and then measured. Measurement points were selected in specific areas, but also considered random. Commands for dimensioning the image are used to determine the length and width of the rectangular shape. The measurements were manually input into a spreadsheet.

2DNCMT Measurement Tests. The other measurement tests performed were performed only on the 2DNCMT since the parts being measured were a known size. The results of each test were processed using Mintab and AIAG Gage R&R and Honest Gage R&R studies were performed.

Equipment Used. Two vision measurement systems were used in the testing process: The 2DNCMT and the Nikon VMA-2520, located in the university Metrology Laboratory.

Reference targets used with the 2DNCMT were: gage blocks, .010 inch miniature feeler gage blade, and a .250 diameter flat washer.

Other tools included tweezers, 3X textile magnifying glass, masking tape, and double-sided tape.

Procedure for Using the 2DNCMT. See Appendix E. 2DNCMT Operating Procedure

Procedure for Using the Nikon VMA-2520 Vision Measurement System. Because the sampling size in the project is very small, the Nikon was used in manual mode. User's manuals and instructions on how to measure parts using the VMA-2520 are available from Nikon Metrology.

Sample Parts Used. Four sample parts were used in the measurement tests: a plastic spacer, two paper part designs, and a plastic micro part**.**

The plastic spacer, as shown in Figure 4.2, was used to compare the measurements produced by the Nikon and 2DNCMT. This part was used because of its sharp, easy to see edges.

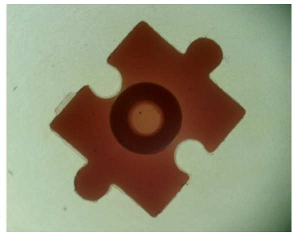

Figure 4.2 Plastic Spacer Part

The paper models used in the measurement tests were designed to determine how well the 2DNCMT worked with thin parts and small features. The paper models, as shown in Figure 4.2, were precision CNC cut using 65-pound cardstock. Two patterns were generated for the experiment: angular and round.

A Silhouette SD CNC paper cutter was used for this project using a 0.3mm knife (0.0118 in). The knife leaves an approximately .012 inch wide kerf that contains microscopic tears and deformations. The program used to cut the parts had no offset so the knife cut right on the line. The parts were double cut to get the cleanest edges. A +/-.007 inch tolerance is given to the paper parts to compensate for the kerf.

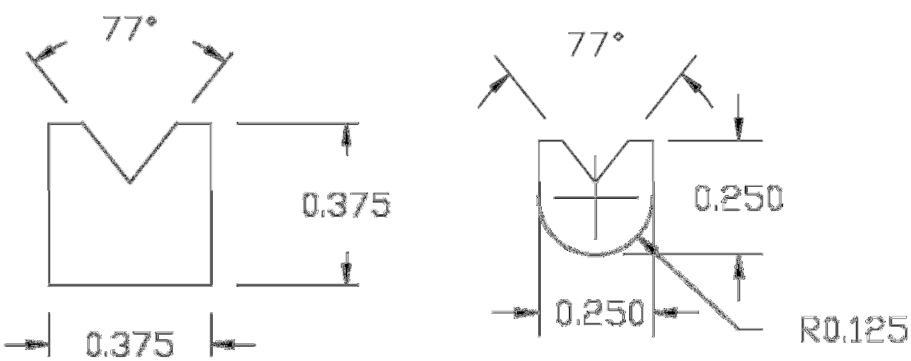

Figure 4.3 Paper Part Dimensions

A micro part selected was used for a size study to determine how well images produced by the 2DNCMT will look and measure in the 2D CAD environment. The micro part (see Figure 4.4) was a small round plastic part with a diameter of approximately .083 inches. Only the outside diameter would be measured.

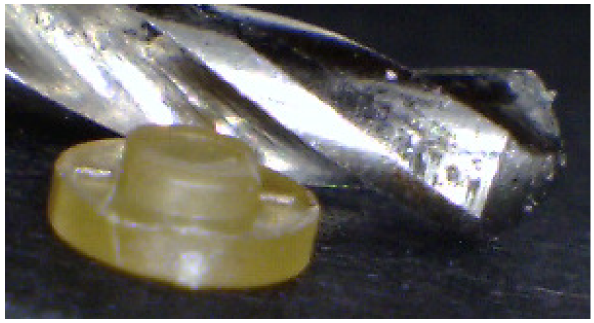

Figure 4.4 Micro Part with 1/16 (.0625 In.) Drill Bit in Background as Reference. Sample Part Courtesy of Accumold Corporation.

Sampling Methods and Procedures. Sample sizes were as follows:

- Ten plastic spacers used in the 2DNCMT – Nikon Comparison Test were randomly selected from a group of thirty parts.
- Ten large paper part samples were randomly selected from a group of forty parts.
- Ten small paper part samples were randomly selected from a group of forty parts.
- Ten micro parts were randomly selected from a group of twenty-five parts.

Measurement methods used were as follows:

- For the 2DNCMT – Nikon Comparison Test. 2 operators, 2 trials, 10 parts. Parts measured in random order. The trials were performed on different days.
- For the 2DNCMT paper and micro part tests: 3 operators, 2 trials, 10 parts. Parts measured in random order. The trials were performed on different days.

Measurement Analysis Methods. The following analysis methods were used for each measurement test:

- Measurement Uncertainty
- Process Capability (Cp,Cpk)
- AIAG Gage R&R Study.

- Honest Gage R&R Study

Measurement Uncertainty. A measurement provides information about an object or process by giving it a number. Uncertainty in a measurement provides information about its quality. "A measurement result is only complete if it is accompanied by a statement of the uncertainty in the measurement" (Bell, 1999).

Measurement is always subject to some uncertainty. Uncertainties can be caused by any number of sources. The more complex the tool, the more uncertainty is added. Figure 4.5 lists some of the possible sources of uncertainty in this project.

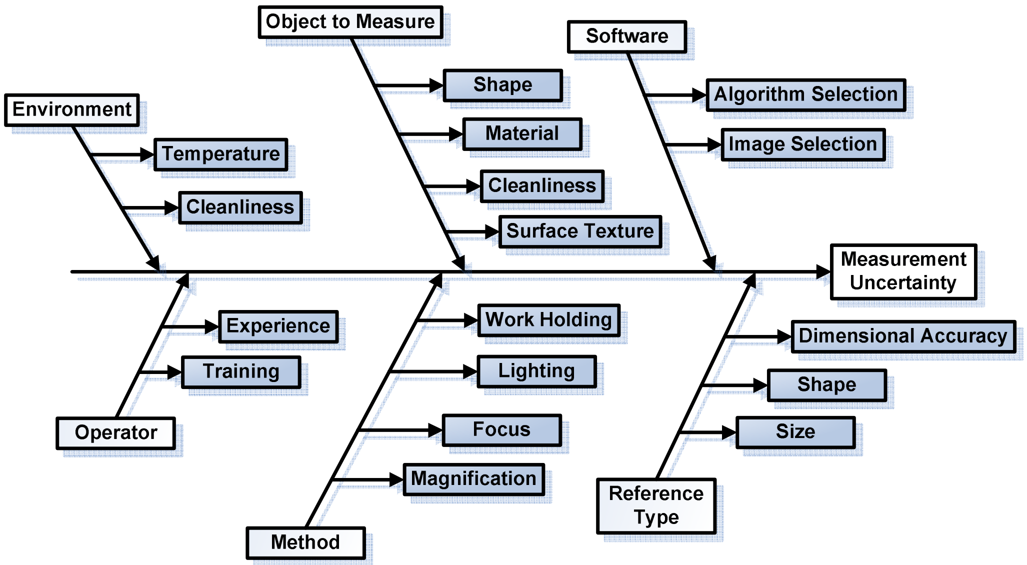

Figure 4.5 Possible Sources of Uncertainty

Some uncertainties cannot be deleted from the problem, but they may be quantified by some sort of numeric ranking and included in the measurement calculation. Others may be dismissed as negligible depending on the problem being researched. Regardless, it is good practice to utilize “traceable calibration, careful calculation, good record keeping and checking”. [Only] When the uncertainty in a measurement is evaluated and stated, the fitness for purpose of the measurement can be properly judged. (Bell, 1999)

The Inter-Laboratory Comparison Test (ISO Guide 43-1) was a good fit for this project. It is a Type A,B measurement uncertainty test using the Type A statistical analysis and incorporating the Type B 10% gage increment. The test was originally designed to determine laboratory proficiency for accreditation purposes and to provide an independent proof of confidence in the process or tool. The test was designed to use multiple operators, testing the same materials and using the same procedures. A MS-Excel spreadsheet provided with The Metrology Handbook (Bucher, 2004) was used for this analysis.

Process Capability. There are several process capability methods. The ones used for this project were Cp and Cpk. Cp and Cpk calculations provide the following: Cp measures variation, Cpk measures how close the readings are to nominal. An Excel spreadsheet provided with Quality Control, 8th ed., (Besterfield, 2009) was used for this analysis.

Gage R&R Sampling and Procedure. Gage R&R Studies were performed to determine the repeatability and reproducibility of the 2DNCMT. Repeatability is defined as the ability of the same gage to produce consistent measurements no matter how many times the same operator repeats the measurement. Reproducibility is the defined as the ability of the gage to give consistent measurements regardless of who performs the measurement.

The traditional Gage R&R method was developed in the early 1960s. Since then it has gone through numerous revisions and owners and is currently supported by the Auto Industry Action Group (AIAG) of the American Society for Quality. The traditional Gage R&R, now called the AIAG Gage R&R is a very conservative gage analysis which, according to Donald Wheeler (2009), loses its effectiveness as a good analysis tool after Step 5, when the AIAG Gage R&R study method's calculations of percentages of variation do not add up to 100%.

In the Honest Gage R&R Study, Donald Wheeler proposed modifications to the calculations so that the percentages of variance add up to 100%, nothing is lost, and it opens up the ultraconservative guidelines used by the AIAG Gage R&R Study to allow more part measurements to pass.

The AIAG Gage R&R and Honest Gage R&R study methods were used to measure and analyze the test parts. With the exception of the Nikon - 2DNCMT comparison test, all Gage R&R studies were are performed using 3 operators running two trials of 10 parts in random order.

In the AIAG Gage R&R Study, the following guidelines, shown in Table 4.2, are used to determine what the percentages of total variation mean:

Table 4.2

AIAG Gage R&R Guideline Ratios

Classification	GRR	ICC
Good	0% - 10%	99% - 100%
Marginal	10% - 30%	91% - 99%
Unacceptable	30% - 100%	0% - 91%

Wheeler provided a simple chart to help understand the correlation between the Combined Repeatability & Reproducibility (CRR) on the Total Variation and the Intraclass Correlation Coefficient (ICC), which is the square of the Product Variation of the Total Variation, and the traditional AIAG Gage R&R guideline ratios. See Figure 4.5.

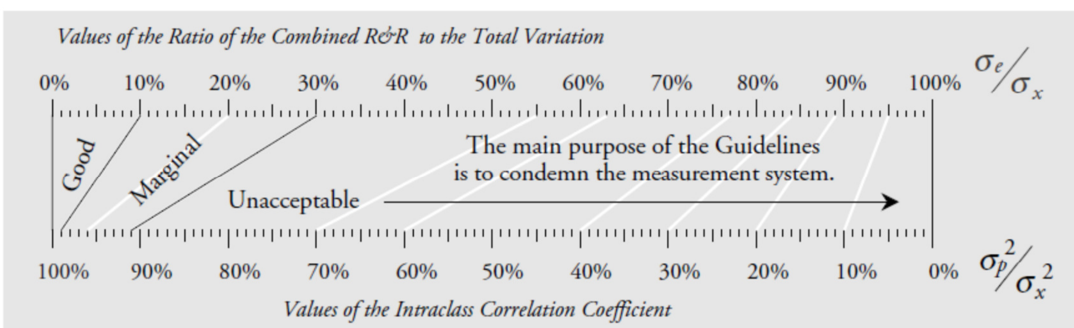

Figure 4.6 A Graphic View of the Extremely Conservative AIAG Gage R&R Ratios. (Wheeler, 2009)

The percentages of total variation for the AIAG Gage R&R Study can be found in the %Study Var column in the Minitab report by using the Xbar and R option in the Crossed gage R&R study. The values are highlighted in yellow in Figure 4.6.

```
                                  Study Var  %Study Var  %Tolerance
Source               StdDev (SD)   (6 * SD)       (%SV)  (SV/Toler)
Total Gage R&R         0.0038927  0.0233562       97.74      233.56
  Repeatability        0.0012612  0.0075672       31.67       75.67
  Reproducibility      0.0036827  0.0220963       92.46      220.96
Part-To-Part           0.0008427  0.0050565       21.16       50.56
Total Variation        0.0039829  0.0238973      100.00      238.97
```

Figure 4.7 Example of AIAG Gage R&R Study Data Generated using Minitab

The Honest Gage R&R Study uses same relationship between the ICC and CRR values as the AIAG Gage R&R Study, but increases the number of guidelines from three to four to describe the relative utility of the measurement system (see Table 4.3). The four classes allow less than perfect data to be used to improve production processes and utilizes the Western Electric Handbook (WEH) Rules for Control Charts to help determine monitor class. The relationship is shown in Figure 4.8.

Table 4.3

Honest Gage R&R Guidelines

Monitor Class	CRR	ICC	Comments
1	0% - 45%	100% - 80%	Has at least 99% chance of detecting a 3 Standard Error (SE) shift in the process using Rule 1 from the WEH.
2	45% - 71%	80% - 50%	Has at least 98% chance of detecting 3 SE shift using rule 1 alone, virtually certain using rules 1, 2, 3 & 4 from the WEH.
3	71% - 89%	50% - 20%	Has at least 91% chance of detecting 3 SE shift using rules 1, 2, 3 & 4 from the WEH.
4	89% - 100%	20% - 0%	Do not use.

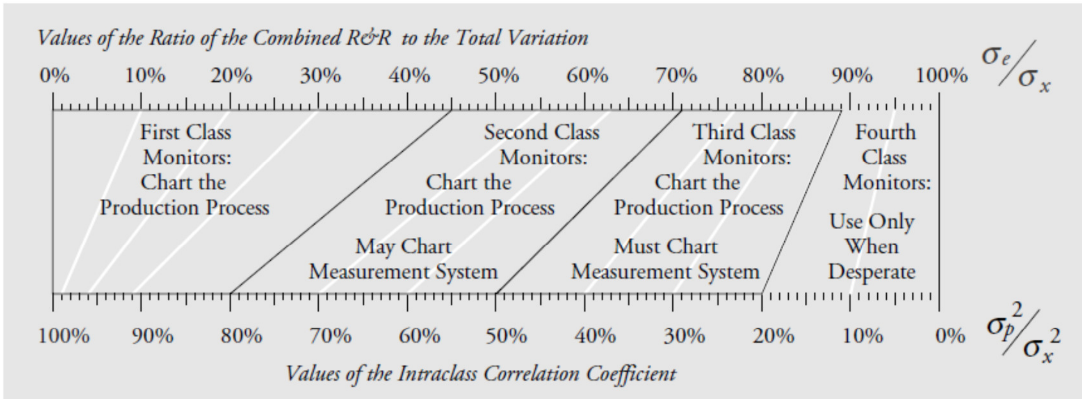

Figure 4.8 The Four Classes of Process Monitors used in the Honest Gage R&R Study (Wheeler, 2009)

The Honest Gage R&R percentages of variation can found in the % Contributions table in the Minitab report by using the Xbar and R option in the Crossed Gage R&R study. The values are highlighted in yellow in Figure 4.9.

```
%Contribution
Source                VarComp    (of VarComp)
Total Gage R&R      0.0000152    (CRR)  95.52
  Repeatability     0.0000016           10.03
  Reproducibility   0.0000136           85.50
Part-To-Part        0.0000007    (ICC)   4.48
Total Variation     0.0000159          100.00
```

Figure 4.9 Example of Honest Gage R&R Study Data Generated using Minitab

5. TEST RESULTS AND ANALYSIS

This chapter describes the results of experiments performed in order to determine the best equipment and processes for producing measurable images and to prove the dimensional accuracy and precision of the 2DNCMT. Table 5.1 contains the chapter outline.

Table 5.1

Chapter 5 Outline

Section	Title	Description
5.1	Feasibility Study Results	Two feasibility studies were performed: flatbed scanner, and grids and scaling.
5.2	Imaging Techniques	Digital image experiment results including edge detection algorithms, software, and other image enhancement methods to improve the quality of the image.
5.3	Equipment Design	The final design of the Microscope and other hardware used in this project including illumination, reference target, and stage design.
5.4	Measurement Test Results	The results of the four measurement experiments outlined in Chapter 4 are discussed.
5.5	Summary	Analysis of the test data.

FEASIBILITY STUDIES

Two feasibility studies were performed prior to the beginning of this project. The results of the feasibility studies can be found in Appendix N. Feasibility Studies and Results.

COLOR, IR, AND UV FILTERS

Yellow, red and blue filters washed out so hardly a trace of color was visible in the digital images. No discernible difference was noted when using the UV filter. IR filters #750 and #850 and the polarizing filter “fogged” the images. The “fog” turned into noise when the images were processed.

COLOR REFLECTION

Using colored paper as part of the lower illumination provided better image contrast than using colored lens filters. Yellow and white increased the contrast on dark part, but washed out light colored parts. Black works well in eliminating shadows on thick parts. Aluminum foil was very effective in producing bright white backlighting.

EDGE DETECTION ALGORITHMS

Early in the research, Matlab was used for edge detection research. However, once the project budget and scope was set, any purchased software was dropped. Several image enhancement software applications are available for free that can perform this task. Because of budget limitations, the choice of edge detection algorithms was limited to Canny, and Sobel. Thinning or skeletonizing algorithms were limited to Stentiford, Zhang-Suen, and Canny.

Which algorithm to use was dependent on image contrast and image noise. The Canny algorithm seemed to work best for low or evenly contrasted image that could not be easily enhanced with software without losing features. The Sobel edge detection algorithm worked well for high contrast images.

ILLUMINATION

Table 5.2 describes several illumination techniques that were tested in order to determine the best type of illumination for the experiments run for this thesis. Table 5.3 covers analysis of lighting types tested for the 2DNCMT.

Table 5.2

Illumination Techniques tested in this Project

Illumination Type	Description and Results	Quality
Under stage direct	A 9-LED flashlight was used for under stage illumination. The light and dark areas that resulted in images that could not be successfully processed.	Poor
Under stage direct ring light	A 70mm ring light was used to direct light from under the stage. The ring light created a dark spot in the middle of the stage.	Fair
Under stage Indirect ring light	A 70mm ring light facing away from the stage so the illumination is reflected back. Evenly spread generated excellent backlighting and good contrast.	Excellent
Overhead direct	The USB microscope comes with built-in 6-LED illumination. This illumination creates bright spots in the image which are very annoying particularly if the object or target is reflective (shiny).	Poor
Overhead direct ring light	A 70mm ring light was used to direct light down on the object and stage.	Fair
Overhead spherical illumination	A 70mm ring light is place on top of the stage with the object in the center. The illumination is reflected inside a white plastic hemisphere and back at the object. This technique practically eliminated shadows for thick parts. Good when backing objects with black construction paper.	Excellent
Hand-held UV flashlight	A 9-LED UV flashlight was shone on the object at an angle in order to reveal more detail. Managing the flashlight was difficult. A stand is needed to hold the flashlight.	Poor

Table 5.3

Illuminators Tested in this Project

Illuminator	Description	Quality
Ambient light	Too much shadowing.	Poor
Bright white LED flashlight	Produces too much glare. Light is too focused.	Poor
LED green/blue nightlight	Stable, solid backlighting. Could be used in future improvements.	Excellent
LED ring light	Excellent indirect illumination source. This one was selected for all illumination used on the 2DNCMT.	Excellent
UV LED flashlight	Not enough light produced, but good for highlighting light surfaces.	Good

Glare and Light Leakage. Blocking the USB microscope's integrated illumination made a big difference. The USB microscope used in this project is an older model. Newer models come with on/off switches for the illumination. Colored rings surrounding the object being imaged also worked well in blocking light.

Lens Distortion. The demonstration version of a software application called IMATEST was used for testing lens distortion on the USB microscope. The following distortion pattern was detected as shown in Figure 5.12**.**

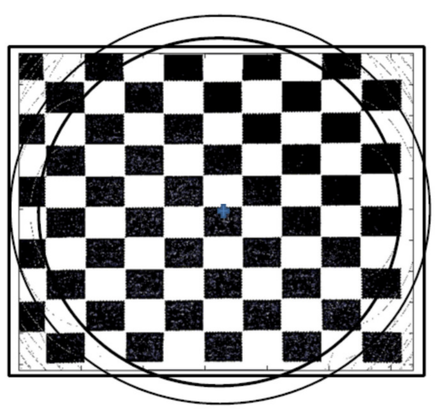

Figure 5.1 Lens Distortion Results

According to the results from the IMATEST Lens distortion test, the lens on the USB microscope has an oval shaped distortion with the center slightly off to the side. The bulk of the image area is minimally distorted with vignetting out at the edges. Objects must be imaged close up and as close to the center of the image area as possible. This holds true. In early tests, known reference targets were placed at the extreme corners of the image and dimensions of the images in the 2D CAD environment were inaccurate.

SOFTWARE

Table 5.4 lists the final software selected for this thesis project. The final software was selected for the following reasons:

- Open source or freeware.
- Actively supported
- Easy to understand and use.

Table 5.4

Final Software Selection

Software	Review
DraftSight	DraftSight is freeware with registration. This software is an AutoCad-clone with a limited command set.
ImageJ	Open source software actively supported by the NIH. Excellent for processing and enhancing microscopic images.
Win TOPO	Win TOPO is a freeware provided by the SoftSoft company. It is used to convert digital images into vector graphics. It Can also perform edge detection and skeletonization.

MEASUREMENT TEST RESULTS

The following measurement tests were performed:

- Test 1 compared the repeatability and reproducibility of the 2DNCMT and the Nikon VMA-2520 using the same parts.
- Test 2 measured the size and angularity of the larger paper part.
- Test 3 measured the size and diameter of the small paper part.

- Test 4 tested the ability of the 2DNCMT to produce an accurate image of a micro part.

Each measurement test was analyzed using Process Capability (Cp, Cpk) testing and Measurement Uncertainty analysis using MS-Excel Spreadsheets. AIAG Gage R&R and Honest Gage R&R studies were also performed using Minitab v15. All test data and calculations can be found in Appendix D. Test Data and Results. Additionally an overlay test was performed on sample parts to provide a visual for how well the 2DNCMT performed.

2DNCMT and Nikon VMS-2520 Comparison Test. Data and Gage R&R calculations used for the Nikon-2DNCMT comparison can be found in Appendix D. Test Data and Results. Minitab was used to process both Nikon and 2DNCMT measurement results. Each test was performed using 2 operators, 2 trials, and 5 parts. The test results can be found in Appendix D. Test Data and Results.

X Dimension Analysis. The AIAG Gage R&R results in Table 5.5 for the Nikon X dimension measurement showed that the system used in manual mode had marginal repeatability and unacceptable reproducibility (see Appendix D. Test Data and Results). These results were a surprise but not unexpected. Any number of reasons can cause these results.

The AIAG Gage R&R for the 2DNCMT X dimension measurements for the same parts showed unacceptable repeatability but good reproducibility (see Appendix D. Test Data and Results).

Later measurements using dial calipers showed that the plastic spacers used for this test had a wide range of measurement (see Appendix D. Test Data and Results).

Interestingly, the Honest Gage R&R Combined Repeatability and Reproducibility (CRR) on the Total Variation and the Intra-class Correlation Coefficient (ICC) were very similar as shown in Table 5.6. Unfortunately the Honest Gage R&R Study method showed the X dimension measurement using either machine to be a Class 4 which means both gages are unacceptable for measuring the X dimension of the plastic spacer.

Table 5.5

AIAG Gage R&R X Dimension Results for the Nikon - 2DNCMT Comparison Test

AIAG Gage R&R	NIKON %X	2DNCMT %X
Total Gage R&R (GR&R)	98.29	93.49
Repeatability (EV)	98.29	91.4
Reproducibility (AV)	0	19.63
Part to Part Variation (PV)	18.40	35.5
Total Variation	100	100

Table 5.6

Honest Gage R&R X Dimension Results for the Nikon - 2DNCMT Comparison Test

Honest Gage R&R	NIKON X %Contribution of VarComp	2DNCMT X %Contribution of VarComp
Total Gage R&R (HGRR)	96.62	87.4
Repeatability	96.62	83.54
Reproducibility	0	3.85
Part to Part Variation (HPV)	3.38	12.6
Total Variation (HTV)	100	100
Honest CRR = HGRR / HTV	95.52	87.40
Honest ICC = HPV / HTV	4.48	12.60
Honest R&R Class	4	4

Y Dimension Analysis. The AIAG Gage R&R for the Nikon Y dimension measurement showed that the system used in manual mode had both unacceptable repeatability and reproducibility as shown in Table 5.7. Like the X dimension analysis; any number of reasons can cause these results.

The AIAG Gage R&R for the 2DNCMT Y dimension measurements for the same parts showed unacceptable repeatability and marginal reproducibility as shown in Table 5.7. The marginal reproducibility was unexpected.

The Honest Gage R&R Combined Repeatability and Reproducibility (CRR) on the Total Variation and the Intra-class Correlation Coefficient (ICC) were not close at all (Table 5.8). The calculations show the Nikon as Class 4, unacceptable for the Y dimension measurement. The 2DNCMT is a Class 3, which means a close eye must be kept on the gage. Overall, the Nikon and the 2DNCMT perform about the same.

Table 5.7

AIAG Gage R&R Y Dimension Results for the Nikon - 2DNCMT Comparison Test

AIAG Gage R&R	NIKON %Y	2DNCMT %Y
Total Gage R&R (GR&R)	97.51	80.07
Repeatability	97.51	75.42
Reproducibility	0	26.90
Part to Part Variation	22.16	59.90
Total Variation	100.00	100.00

Table 5.8

Honest Gage R&R Y Dimension Results for the Nikon - 2DNCMT Comparison Test

Honest Gage R&R	NIKON %Y	2DNCMT %Y
Total Gage R&R (GR&R)	95.09	64.12
Repeatability	95.09	56.88
Reproducibility	0	7.24
Part to Part Variation	4.91	35.88
Total Variation	100.00	100.00
Combined R&R	93.82	64.12
Intraclass Correlation Coefficient	6.18	35.88
Honest R&R Class	4	3

Large Paper Part Test. Test data and results for the large paper part can be found in Appendix D. Data and Test Results.

Measurement Uncertainty Test

Table 5.9

Measurement Uncertainty Results for the Large Paper Part

Test	X Dimension	Y Dimension	A Dimension
Measurement and Uncertainty*	.374 ± .004 inches	.376 ± .004 inches	76.0± 2 degrees

Note: Test definitions and formulas can be found in Appendix D. Test Data and Results.

Measurement and Uncertainty are well within specifications. The estimated uncertainty was set at +/-.007 inches for the X and Y dimensions. The specification for the angle was set at +/- 2 degrees.

Process Capability and Tolerance Tests

Table 5.10

Process Capability and Tolerance Test Results for the Large Paper Part

Test	X Dimension	Y Dimension	A Dimension
Cp	1.167, Case I, desirable	1.167, Case I, desirable	1.323, Case I, desirable
Cpk	1.120, good	1.038, good	1.056, good

Note: Test definitions and formulas can be found in Appendix D. Test Data and Results.

Gage R&R Study Results. The AIAG Gage R&R Study (see Table 5.11) shows that the 2DNCMT has unacceptable repeatability and marginal for reproducibility in the X and Y dimension measurements, but had good reproducibility in measuring the angle (A).

The Honest Gage R&R (Table 5.12) shows good reproducibility in X, Y, and A, but unacceptable repeatability in all three measurements. The Honest Gage R&R also identifies the 2DNCMT as 3 Class Monitor meaning that it is good, but should be closely monitored.

Table 5.11

AIAG Gage R&R Results for the Large Paper Part

AIAG Gage R&R	X	Y	A
Total Gage R&R (GR&R)	76.37	88.53	86.98
Repeatability	72.21	86.85	86.98
Reproducibility	24.86	17.13	0
Part to Part Variation	64.56	46.51	49.33
Total Variation	100	100	100

Table 5.12

Honest Gage R&R Results for the Large Paper Part

Honest Gage R&R	X	Y	A
Total Gage R&R (GR&R)	58.32	78.37	75.66
Repeatability	52.15	75.43	75.66
Reproducibility	6.18	2.93	0
Part to Part Variation	41.68	21.63	24.34
Total Variation	100	100	100
Combined R&R	58.32	78.37	75.66
Intraclass Correlation Coefficient	41.68	21.63	24.34
Honest R&R Class	3	3	3

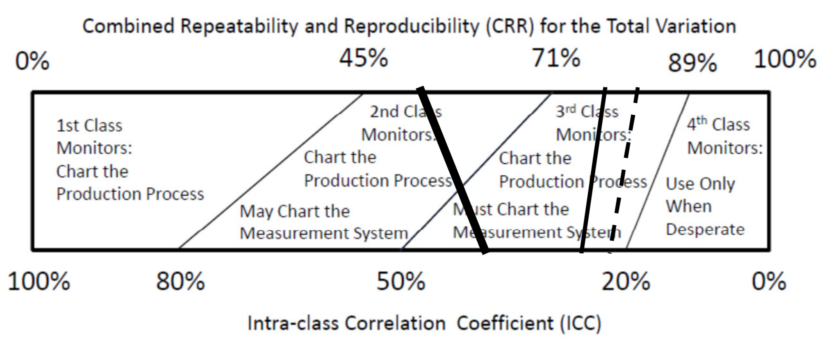

Figure 5.2 Honest Gage R&R results for the Large Paper Part Measurements
Thick Line: X. Thin Line: Y, Dashed Line: A

Small Paper Part Test. Test data and results for the small paper part can be found in Appendix D. Data and Test Results

Measurement Uncertainty Test

Table 5.13

Measurement Uncertainty Results for the Small Paper Part

Test	X Dimension	Y Dimension	D Dimension
Measurement and Tolerance	.250 ± .003 inches	.247 ± .007 inches	.249 ± .004 inches

Note: Test definitions and formulas can be found in Appendix D. Test Data and Results.

Measurement and Uncertainty are well within specifications. The estimated uncertainty was set at +/-.007 inches for the X, Y, and D dimensions. The Y dimension uncertainty is out of specification.

Process Capability Results

Table 5.14

Process Capability Results for the Small Paper Part.

Test	X Dimension	Y Dimension	A Dimension
Cp	2.789, Case I, desirable	2.789, Case I, desirable	2.789, Case I, desirable
Cpk	2.788, good	2.307, good	1.973, good

Note: Test definitions and formulas can be found in Appendix D. Test Data and Results.

Gage R&R Study Results. Data and Gage R&R calculations used for analyzing the data for the large paper part are found in Appendix D. Test Data and Results. Minitab was used to process the measurement results. Each test was performed using 3 operators, 2 trials, and 10 parts. The resulting data is listed in Tables 5.15 and 5.16.

The AIAG Gage R&R Study (Table 5.15) shows that the 2DNCMT has unacceptable repeatability and marginal reproducibility for measuring the X and Y dimensions, but good reproducibility when measuring the diameter (D). The Honest Gage R&R (Table 5.16) identifies the 2DNCMT as good repeatability for measuring X, Y, and D. It is marginal for repeatability in the X dimension measurement. According to the guidelines for the Honest Gage R&R, the 2DNCMT is a Class 3 Monitor meaning that the gage is usable, but must be monitored.

Table 5.15

AIAG Gage R&R results for the Small Paper Part

AIAG Gage R&R	X	Y	D
Total Gage R&R (GR&R)	59.93	66.79	72.61
Repeatability	56.24	65.69	72.61
Reproducibility	20.7	12.1	0
Part to Part Variation	80.05	74.42	68.76
Total Variation	100	100	100

Table 5.16

Honest Gage R&R results for the Small Paper Part

Honest Gage R&R	X	Y	D
Total Gage R&R (GR&R)	35.92	44.61	52.72
Repeatability	31.63	43.15	52.72
Reproducibility	4.28	1.46	0
Part to Part Variation	64.08	55.39	47.28
Total Variation	100	100	100
Combined R&R	35.92	44.61	52.72
Intraclass Correlation Coefficient	64.08	55.39	47.28
Honest R&R Class	2	2	3

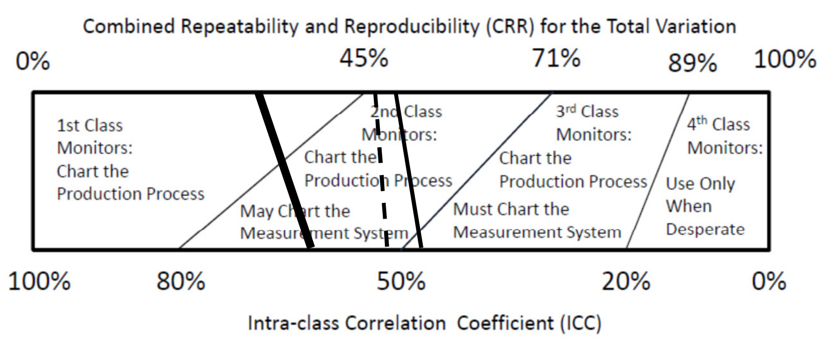

Figure 5.3 Honest Gage R&R results for the Small Paper Part Measurements
Thick Line: X. Thin Line: Y, Dashed Line: A

Micro Part Test. Test data and results for the micro part can be found in Appendix D. Test Data and Results

Measurement Uncertainty Test

Table 5.17

Measurement Uncertainty Results for the Micro Part

Test	D Dimension
Measurement and Tolerance	.0829 ± .0006 in.

Note: Test definitions and formulas can be found in Appendix D. Test Data and Results.

Measurement and Uncertainty are well within specifications. The estimated uncertainty was set at +/-.0008 inches for the D dimension.

Process Capability (Cp,Cpk), and Process and Tolerance, and Precision-to-Tolerance Ratio Tests

Table 5.18

Process Capability Results for the Micro Part.

Test	D Dimension
Cp	1.043, Case I, desirable
Cpk	1.043, good

Note: Test definitions and formulas can be found in Appendix D. Test Data and Results.

Gage R&R Study Results. Data and Gage R&R calculations used for analyzing the data for the micro part are found in Appendix D. Test Data and Results. Minitab was used to process the measurement results. Each test was performed using 3 operators, 2 trials, and 10 parts. The resulting data is listed in Table 5.19.

Both the AIAG Gage R&R Study and the Honest Gage R&R Study show the 2DNCMT having unacceptable repeatability and good reproducibility. The Honest Gage R&R identifies the 2DNCMT as a Class 4 Monitor meaning that it should only be used if desperate.

Table 5.19

AIAG Gage R&R results for Micro Part

AIAG Gage R&R	D
Total Gage R&R (GR&R)	91.61
Repeatability	91.61
Reproducibility	0
Part to Part Variation	40.1
Total Variation	100

Table 5.20

Honest Gage R&R results for Micro Part

Honest Gage R&R	D
Total Gage R&R (GR&R)	83.92
Repeatability	83.92
Reproducibility	0
Part to Part Variation	16.08
Total Variation	100
Combined R&R	83.92
Intraclass Correlation Coefficient	16.08
Honest R&R Class	4

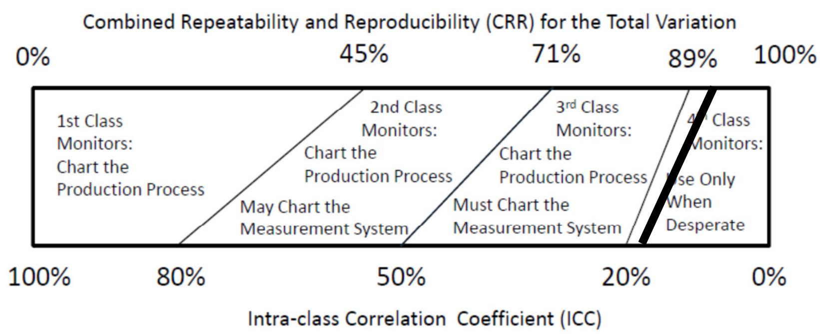

Figure 5.4 Honest Gage R&R Results for the Micro Part Diameter Measurements

MEASUREMENT TEST ANALYSIS

The Nikon-2DNCMT Comparison Test showed that the two systems were almost equal in both AIAG Gage R&R and Honest Gage R&R. This was not a complete surprise. The Nikon VMA-2520 vision measurement system resides in the University Metrology Laboratory with uncontrolled access and no calibration label.

After it was proven that the Nikon VMA-2520 was not going to provide much insight, the rest of the measurement tests were run exclusively on the 2DNCMT. Tables 5.21 and 5.22 summarize the Gage R&R results for the large paper part, small paper part, and micro part measurement tests.

Table 5.21

Combined AIAG Gage R&R Results for the Large, Small, and Micro Parts

	Large Paper Part			Small Paper Part			Micro
AIAG Gage R&R	X	Y	A	X	Y	D	D
Total Gage R&R (GR&R)	76.37	88.53	86.98	59.93	66.79	72.61	91.61
Repeatability	72.21	86.85	86.98	56.24	65.69	72.61	91.61
Reproducibility	24.86	17.13	0	20.7	12.1	0	0
Part to Part Variation	64.56	46.51	49.33	80.05	74.42	68.76	40.1
Total Variation	100	100	100	100	100	100	100

Table 5.22

Combined Honest Gage R&R Results for the Large, Small, and Micro Parts

	Large Paper Part			Small Paper Part			Micro
Honest Gage R&R	X	Y	A	X	Y	D	D
Total Gage R&R (GR&R)	58.32	78.37	75.66	35.92	44.61	52.72	83.92
Repeatability	52.15	75.43	75.66	31.63	43.15	52.72	83.92
Reproducibility	6.18	2.93	0	4.28	1.46	0	0
Part to Part Variation	41.68	21.63	24.34	64.08	55.39	47.28	16.08
Total Variation	100	100	100	100	100	100	100
Combined R&R	58.32	78.37	75.66	35.92	44.61	52.72	83.92
Intraclass Correlation Coefficient	41.68	21.63	24.34	64.08	55.39	47.28	16.08
Honest R&R Class	3	3	3	2	2	3	4

Recall that repeatability is defined as the ability of the same gage to produce consistent measurements no matter how many times the same operator repeats the measurement. Reproducibility is the defined as the ability of the gage to give consistent measurements regardless of who performs the measurement. The following guidelines are used to understand the relationship between Gage R&R repeatability and reproducibility:

- If repeatability is large compared to reproducibility, the gage needs maintenance, redesign, or there is excessive within-part variation.
- If reproducibility is large compared to repeatability, the operator needs training in how to use and read the gage (Besterfield, 2009, p. 279)

The AIAG Gage R&R study (see Table 5.21) declared the 2DNCMT unacceptable with repeatability over 30% and reproducibility between 10% and 30% in most cases. The Honest Gage R&R study analysis (see Table 5.22) showed that the 2DNCMT had marginal repeatability and marginal reproducibility, and declared the gage marginal but usable so as long as the production process and measurement system were carefully monitored.

Table 5.23 summarizes the Process Capability results for the large paper part, small paper part, and micro part measurement tests. Recall that Cp measures variation, Cpk measures how close the readings are to nominal.

Table 5.23

Combined Process Capability Results for the Large, Small, and Micro Parts.

	Large			Small			Micro
Process Capability	X	Y	A	X	Y	D	D
Cp*	1.167	1.167	1.323	2.789	2.789	2.789	1.043
Cpk**	1.120	1.038	1.056	2.788	2.307	1.973	1.043

Note: *Case I indicates that Cp>1 and the process is desirable and in control. Case II means Cp=1.00 and the process is equal to the specification but can go out of control if there is a shift. Case III means that Cp<1 and is undesirable. ** If Cpk<1.00 then process does not conform to specification. If the Cpk=1.00 then the process producing the product conforms to specifications. If Cpk>1.00 then the process is good, but a large Cpk may also mean the tolerance is too small.

Cp values show that the gage is good and in control when the mean is centered. Cpk values show that the most of the time the process is in control even if the mean is not centered. Overall, the 2DNCMT passed the process capability test.

In most cases, the measurement uncertainty for each dimension fell inside the specification limits for the parts, as shown in Table 5.24. The control charts in Appendix D. Test Data and Results provide visual proof.

Table 5.24

Anticipated and Actual Measurement and Uncertainty Results for the Large, Small, and Micro Parts.

Dimension	Anticipated Measurement and Uncertainty	Measurement Test Results
Large X	.375 ± .007	.374 ± .004 inches
Large Y	.375 ± .007	.376 ± .004 inches
Large Angle	77 ± 3 degrees	76.0 ± 2 degrees
Small X	.250 ± .007	.250 ± .003 inches
Small Y	.250 ± .007	.247 ± .007 inches
Small Diameter	.250 ± .007	.249 ± .004 inches
Micro Diameter	.0820 ± .0008	.0829 ± .0006 inches

6. CONCLUSION

The objective of this research was to design and build a two-dimensional vision-based measurement tool for less than $500US using off-the-shelf components and simple household tools. The tool was designed to be a low-cost disruptive innovation in an industry known for very expensive high cost measurement equipment. The objective was not to replace or compete with these manufacturers, but to offer an “entry level” model that could be used for getting an understanding of the technology without a large investment.

The components that make up the microscope design: the power drill support, compound table, USB microscope, and LED ring lights used for the upper and lower illumination were not modified and can easily be used in other projects. The C-clamp used for fine Z-axis adjustment was modified but still usable for other applications. The software selected can also be used other purposes.

The total cost of the project was $490.13. The budget also covered the cost of mistakes and items purchased for experiments. Examples include purchased software that did not operate as claimed and designing and fabricating a miniature Sarrus linkage for elevating reference targets. Gage blocks took the place of the Sarrus linkage.

While the microscope design was fairly straightforward, it took a bit of imagination to design the upper and lower illumination in a way that did not require machine tools or expensive parts.

Understanding the process of converting a digital image into a calibrated 2D CAD drawing and then finding the right combination of free software was time consuming. Much of the software researched and tested were demonstration versions with a finite number of uses, watermarks that interfered with the images, or were inconsistent in operation. The final software selected was all very popular, actively supported open source and freeware.

While the results from testing the 2DNCMT were very promising, the prototype did not meet all expectations in imaging, but performed better than expected in measurement. The majority of the measurements made during testing fell within a 95% confidence level.

The Gage R&R studies proved that while the gage was poor in repeatability, reproducibility was generally okay. The reasons for poor repeatability were the inconsistency of the edges of the CNC-cut paper parts and operator instructions. These inconsistencies can be observed in the overlay examples Chapter 5. Test Results and Analysis. Using better objects for the experiments would have made a difference. Early experiments with proved that the 2DNCMT could be consistent. Measurement uncertainty calculations show the original, anticipated part measurements and tolerance were relatively close. Process capability analysis shows the process was in control.

Future improvements for the 2DNCMT include: A review of the process to determine best practices for generating images, and a design of experiments to reduce variation due to environmental interference, object shape, measurement methods, and reference target shapes.

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APPENDIX A

BUDGET

This project was started with an initial budget of $500. The final total came to $490.13. See Table A.1. No University resources or funding were used in this project. Book purchases, shipping charges and sales tax are not included in the overall cost.

Table A.1

Estimated Initial and Final Expenditures

Description		Estimated Expenditures	Final Expenditures
Hardware		$450.00	$466.23
Software		$50	$23.90
	Total	$500	$490.13

There was an expectation that some software would need to be purchased for this project. During the research phase a number of possible software packages ranging from $19-$300 were evaluated. Two were purchased for a total cost of $23.90 ($11.95 each). The purchased software did not work as advertised and was not used in the project. There was some pressure to use software provided by the University to process digital images and AutoCad. None of this software was used at any time during the project because it fell outside the project boundaries.

Some hardware purchases were for experiments that the author felt were necessary to perform. In this case it was photographic filters (IR, UV, FL, polarized), diopters, and a UV flashlight (all purchase via Amazon.com). Total cost: $51.96.

Sometimes a wrong turn is taken during the research phase. Initially, the USB microscope was attached to a vernier height gage. To test out color backgrounds, a small vise and a package of LED nightlights were purchased. This experiment provided information, but none of the items purchased would be used in the final design. The total purchases: Nightlights $7.99 (Amazon.com) and articulated vacuum vise $16.99 (Harbor Freight) = $24.99. Tables A.2 and A.3 itemize hardware and software expenses.

Table A.2

Hardware Purchases

Qty	Item	Unit Price	Total
1	Proxxon Micro Drill Stand (Mb140/S)	$48.00	$48.00
1	Proxxon Compound Table (Kt70)	$96.99	$96.99
1	Celestron USB Microscope (44302)	$39.98	$39.98
1	#3 Conduit Hanger	$1.99	$1.99
1	3” C-Clamp	$2.99	$2.99
2	3” Pvc Drain End Cap	$1.05	$2.10
1	2-Ft 3” ID Schedule 40 PVC	$2.99	$2.99
1	UV LED Flashlight	$8.00	$8.00
11	#10-32 Allen Screws	$0.75	$8.25
2	T10 21-LED White Light (70mm Diameter)	$4.84	$9.68
4	Radio Shack Model 27-411 4-Aaa Enclosed Battery Holders	$1.99	$7.96
20	Aaa Batteries	$0.50	$10.00
2	4-Gang Terminal Strips	$3.00	$6.00
2	2- LED T10 Wedge Socket	$3.99	$7.98
1	*Wallet Sized 2x Fresnel Lens	$5.33	$5.33
1	*8x10 Sheet Acrylic	$1.99	$1.99
1	3”X4” Glass Picture Frame	$0.95	$0.95
1	2.5” X 3.5” Galss Picture Frame	$1.50	$1.50
1	Gage Block Set	$69.95	$69.95
1	Mini Feeler Gage Set	$11.59	$11.59
1	Green Masking Tape	$4.72	$4.72
1	Card Stock	$5.00	$5.00
1	Medicine Boxes	$3.50	$3.50
1	*Mini Laser Level	$6.95	$6.95
1	Wiffleball Softball	$0.95	$0.95
1	3-1/2” Dia Practice Tee Ball	$2.95	$2.95
1	*Carson Zorb (USB Microscope)	$29.00	$29.00
1	*Photographic Filters (IR, UV, FL, Polarized), Diopters	$32.03	$32.03
1	*Photographic Diopters	$11.93	$11.93
1	*LED Nightlights	$7.99	$7.99
1	*Articulated Vacuum Vise	$16.99	$16.99
		Total	$466.23

Note: * These items were not used

Table A.3

Software Purchases

Qty	Item	Unit Price	Total
1	Smart-Cam DXF	$11.95	$11.95
1	Smart-Cam CMM	$11.95	$11.95
		Total	$23.90

Table A.4 identifies the parts and cost to build the prototype 2DNCMT. The final cost for the prototype was $246.49.

Table A.4

Prototype Parts List and Cost

Qty	Item	Unit Price	Total
1	Proxxon Micro Drill Stand (Mb140/S)	$48.00	$48.00
1	Proxxon Compound Table (Kt70)	$96.99	$96.99
1	Celestron USB Microscope (44302)	$39.98	$39.98
1	#3 Conduit Hanger	$1.99	$1.99
1	3" C-Clamp	$2.99	$2.99
1	3" Pvc Drain End Cap	$1.05	$1.05
1	2-Ft 3" ID Schedule 40 PVC	$2.99	$2.99
2	T10 21-LED White Light (70mm Diameter)	$4.84	$9.68
4	Radio Shack Model 27-411 4-Aaa Enclosed Battery Holders	$1.99	$7.96
16	AAA Batteries	$0.50	$8.00
1	4-Gang Terminal Strips	$3.00	$3.00
1	LED T10 Wedge Socket	$3.99	$3.99
1	3"X4" Glass Picture Frame	$0.95	$0.95
1	Green Masking Tape	$4.72	$4.72
1	Card Stock	$5.00	$5.00
1	Wiffleball Softball	$0.95	$0.95
11	#10-32 Allen Screws	$0.75	$8.25
		Total	$246.49

APPENDIX B

MACHINE BUILD

INTRODUCTION

Appendix B discusses the design and building of the 2DNCMT. The goal was to utilize off-the-shelf hardware as much as possible. Using off-the-shelf hardware makes it easier to repair and modify using simple tools.

HARDWARE ANALYSIS

Microscope Support Frame. Part of the task of designing the 2D Vision-based measurement tool was how the USB microscope was going to be supported and what functions it should perform. Some of the attributes desired included: compact design, portability, adaptable, easily repairable, ability to rotate the USB microscope, boom stand (preferred), and easy to raise and lower the microscope. Another important requirement was that the stand had to be as inexpensive as possible.

An internet research revealed that inexpensive USB and digital microscopes came with simple stands or no stands at all (Figure B.1). These stands were difficult to use and not particularly rigid. The price for an inexpensive USB microscope, with or without a stand, ranged from $60 - $500.

Figure B. 1 Examples of Stands for Inexpensive USB Microscopes
Left: USB stand with a heavy base and cradle to hold the microscope. Middle: Flexible metal tubing is creatively used to hold this microscope. Right: This microscope came with no stand at all.

Slightly more expensive USB and digital microscopes come with better stands and better microscopes. The stands shown in Figure B.2 could be purchased individually, but cost about $250.

Figure B. 2 Examples of More Expensive Digital Microscope Mounts
Note: Practical Tools catalog (2011) Left: Track stand with singular rack and pinion adjustment. Right: Boom stand with fine adjustment.

High-end USB and digital microscope stands get quite complicated. The Keyence VHX-1000, as shown in Figure B.3, is an excellent example of an all-purpose microscope stand.

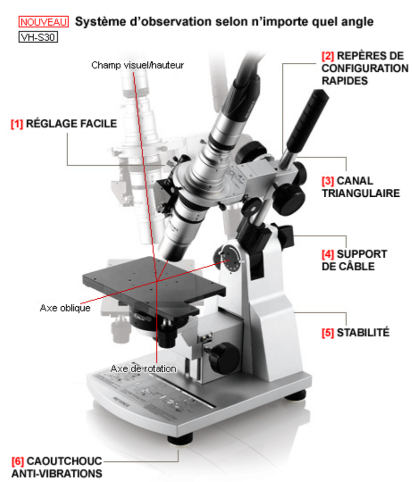


Figure B. 3 Keyence VHX-1000 (2010) Digital Microscope Stand.
The stand allows the USB microscope infinite positions in the X-Z axis. The stage can also be turned and tilted. It also has rack and pinion coarse and fine height adjustments and built-in under-stage illumination.

The inexpensive USB microscope stands were immediately taken out of consideration due to difficult in positioning the USB microscope properly. The intermediate stands and the Keyence VHX-1000 were examined more closely.

A boom stand was wanted so that the 2DCMT would be more versatile. Boom mounts have one flaw: that is that the boom has no control over how much the microscope mount can rotate in the XY-axis because it uses a compression fitting around a round rod. After researching boom microscopes this was determined not to be a problem.

The Keyence stand also has capability to rotate the USB microscope in order to take images for 3D applications.

Cost Analysis. Initially, the idea was to design and fabricate a custom USB microscope stand. After the budget was set it became more apparent that the best way to was purchase as much of the 2DNCMT hardware as possible. Research for the materials costs for a rack & pinion, simple boom stand and some COTS alternatives was performed. See Tables B.1 and B.2 for estimated material costs. Labor and design costs were not included in the estimated costs for the rack & pinion and boom-style stands. If these costs were included, the project's budget would have been quickly depleted and the project would end.

Table B.1

Estimated Cost for a Rack & Pinion USB Microscope Stand

Item	Price (McMaster Carr)
Gear: 16-Tooth 9/16	$13.89
Rack 16-Tooth, ½" X 12"	$24.42
1"X1"X12" Steel Post, 1018	$13.70
4" X 8" X 1" Aluminum Plate	$34.94
Total:	$86.95

Table B.2

Estimated Cost for a Simple Boom-Style USB Microscope Stand

Item	Price (McMaster Carr)
1” Collar With Set Screw	$1.47
1”Dia X12” Steel Post, 1018:	$34.87
4” X 8” X 1” Aluminum Plate:	$34.94
Total:	$71.28

Table B.3

Other Off-The-Shelf Products Considered To Be Good Substitutes

Item	Price
Vernier Height Gage (mm)	$94.98
The following are Mini Drill Stands	
Proxxon Tech 28606 MICROMOT Drill Stand MB 140-S*	$57.00
Dremel® Articulating Drill Press (220-01)	$53.99
Jameco BenchPro Mini Drill Stand	$25.95

Note: *The Proxxon mini drill stand is designed to accommodate a compound Table.

Compound Table. Early in the project it became apparent that aligning objects to be examined was going to be an issue and a stable platform was needed. With traditional microscopes, the object to be examined is first mounted to a glass slide or some sort of fixture and then placed on a platform located between the lens body and illumination called a stage. The stage includes clips for securing the mounted object. The stage is either fixed or compound. Fixed stages require the user to look through the eyepiece and manually align the object to viewing field. Compound stages allow the user to move the stage by rotating micrometer screws mounted in the x and y axes.

Because the selected USB microscope did not come with a stand, research was necessary to determine the most cost effective and efficient method for aligning the object being examined with the microscope. One of the project requirements was to limit the size of the objects being examined to 1-inch diameter or less, but one also has to consider future uses. One of the items on the wish list was to be able to use the same hardware for 3D laser scanning. That meant that the stage had to moveable and relatively large. Compound milling Tables and cross slide vises were considered as possible stages or as a base for a removable stage.

A cross slide vise is actually two slide vises combined as shown in Figure B.4. One vise controls X-direction movement, the other controls Y-direction movement. This type of vise is most commonly used at manual drill press stations. Figure 7 provides additional information on how a cross slide vise is constructed.

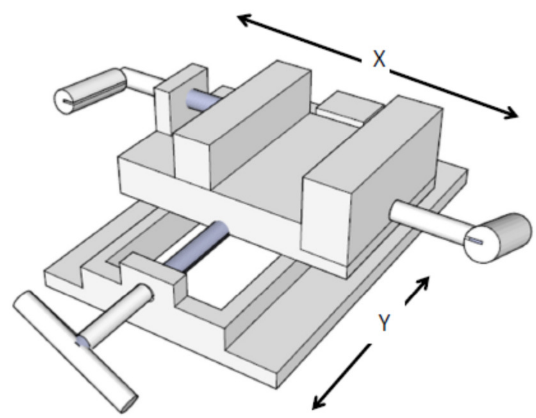


Figure B. 4 Slide Vise

A Compound milling Table, also called an XY Table, is used in precision milling operations. The design is similar to a cross slide vise except that top surface is an accurately ground, finished surface with t-slots for mounting a variety of fixtures, jigs, and vises. Figure B.5 shows a compound milling Table.

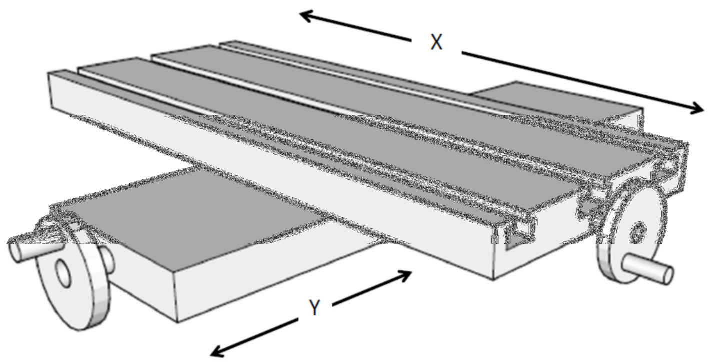


Figure B.5 Compound Milling Table

REFERENCE TARGETS

The problem with any measurement method is accuracy. The calibration of measurement equipment is vital. This 2D vision-based measurement tool can be used in a climate controlled metrology lab, but the goal was to design it for use by individuals that do not have access to a climate controlled lab conditions.

Target Rings. The use of precision machined rings for calibration is a new idea. The idea is to use either the ID or OD for image calibration. Figure B.6 shows examples of how the rings may be used.

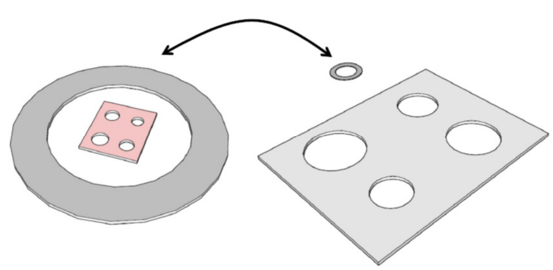


Figure B.6 Dots and Squares

The Dots and Squares (Figure B.7) format was, at first, independently developed and designed. Later on it was found that Edmunds Optics (Edmunds Optics, 2011) sold a vision system calibration slide using the same technique, but in a different way. The concept was not new, but the how it was used in this project was.

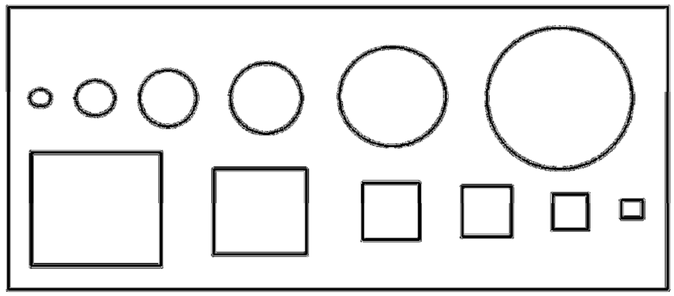


Figure B.7 Example of a Dots and Squares Slide used in the Project

Early in the project the idea of using slides with precision cut square and dot shaped holes to use as reference target was devised and four variations of Dots and Squares were devised and tested. Table B.4 lists the variations and materials used. The Dots and Squares Slides worked so well, the concept was carried on to the final 2DNCMT construction. The final design used black cardstock.

Table B.4

Materials used to Make Dots and Squares Sides for this Project.

Variation	Description
1	Black construction paper and white card stock on paper board. This method was the least expensive and has potential. Construction paper has a very coarse structure and the CNC paper cutter tore the edges slightly.
2	Black vellum on white vellum. This method was slightly more expensive than Variation 1. The vellum sheets, having a matte finish, reduced noise considerably and made it easy to get good contrast in the images. Vellum is a high quality paper with a very fine structure. The paper cut well and the edges are sharp.
3	Vinyl decal material on glass. The vinyl decal material was very shiny so images contained speckles (noise) from the glare. Matte finish vinyl decal material is available.
4	Automotive window film on glass. A sample of limousine tint was used to test this option. The film cut well and edges were sharp.

ALTERNATE MEASURING DEVICES

Several other objects were also used for reference targets: flat washers, min and large feeler gages, and gage blocks. All were measured using other metrology tools. Of the targets, the mini-feeler gage strips and flat washers provided the best results.

SETTING UP THICK PARTS FOR MEASUREMENT

In this project, gage blocks were used for putting reference targets in the same plane as the surface of a thick part being measured. The method, shown in Figure B.8 is quite simple.

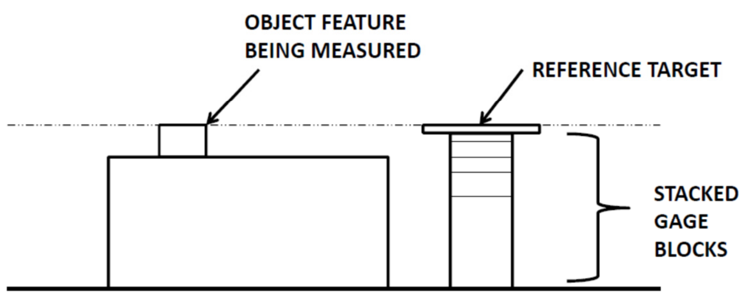


Figure B.8 Gage Block Stack Up for Reference Target

ILLUMINATION

Upper Illumination. There are several methods used for upper illumination in machine vision and stereomicroscopy. See Appendix H. Lighting System Analysis and Design for more design information. Most machine vision systems use ring lights, but a quick internet search concluded that the price of off-the-shelf ring light illumination was more than the project budget would allow. Inexpensive 70mm ring lights were finally located.

The final illumination design used a 70mm ring light placed directly on the stage with the object being examined in the center. A white plastic hemisphere was attached to the USB microscope mount and the USB microscope's integrated illumination was blocked. The hemisphere scatters the illumination and washes out shadowing. Figure

B.9 is an example of how well this technique works. See Appendix C. Design Data for dimensions for the spherical cover.

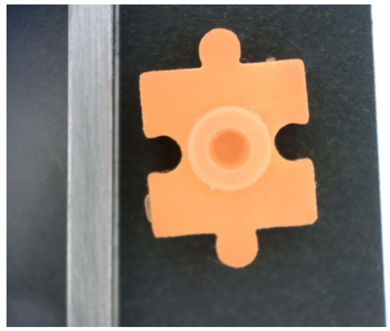


Figure B.9 Reflective Illumination using Spherical Diffusion

Another upper illumination design used a fixture that allowed the LED ring light to point straight down. Because the ring of LEDs was larger than any objects being examined, no glare was produced. This technique, used in conjunction with a white plastic ring placed on the stage, produced almost as good of lighting as the spherical illumination and was a little easier to work with.

Final upper illumination design information is found in Appendix H. Lighting System Analysis.

Lower Illumination. Lower illumination was more difficult to design than the upper illumination. The end result was using a 70mm ring light mounted inside a plastic ring with the LEDs pointed away from the stage. In this way the light quality could be controlled by using different materials as reflective surfaces. Aluminum foil and white, black, and yellow card stock was tested. Paper cones were also devised to help reflect the illumination to the center of the ring.

Final lower illumination design information is found in Appendix H. Lighting System Analysis.

Previous Lower Illumination Experiments. Prior lower illumination experiments included LED nightlights, a bright white 9-LED flashlight, and a UV 9-LED flashlight, all with varying degrees of success. In Figure B.10 examples of the LED nightlight backlighting are shown. In Figure B.11 images from the bright white 9-LED flashlight backlighting experiment are shown.

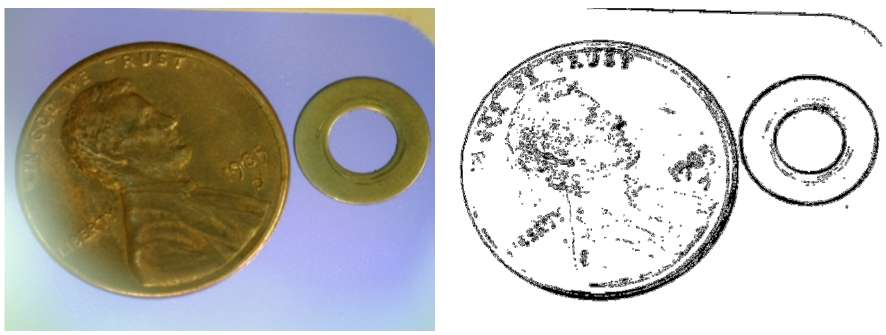


Figure B.10 Night Light Backlighting
Left: Original Image. Right: Image after Edge Detection.

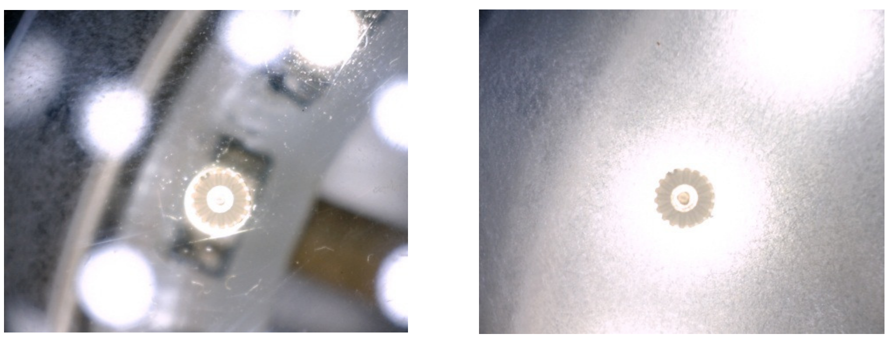


Figure B.11 LED Flashlight Backlighting

B.7 USB Microscope

The USB microscope selected for this project was the Celestron #44302 USB microscope. The USB microscope was purchased in January 2011 and was declared obsolete by the manufacturer six months later.

MICROSCOPE MOUNT

The Proxxon Tech 28606 MICROMOT Drill Stand MB 140-S was selected for this project. A #3 conduit hanger is used to hold the USB microscope in place.

Microscope Alignment. Microscope alignment is a manual operation.

To make the USB microscope perpendicular to the stage, the microscope is lowered so that the microscope's lens shield is in contact with the stage surface, then the clamp is tightened.

To align the USB microscope to the stage, center the microscope over the compound Table, then move the stage until it is centered under the microscope.

PERSONAL COMPUTER

The USB microscope relies on a host compute to provide power, generate, store, and process images.

2DNCMT ASSEMBLY VIEWS AND PICTORIAL PARTS LISTS

Tools Needed. The following tools are needed to fabricate and assemble the 2D vision-based measurement tool.

- 3/16” drill
- #2 Center drill
- Hack saw
- Power drill
- Bench vise
- Xacto knife
- Box Cutter
- Screw drivers
- Allen wrenches
- ½” open-end wrench

Microscope Frame Assembly

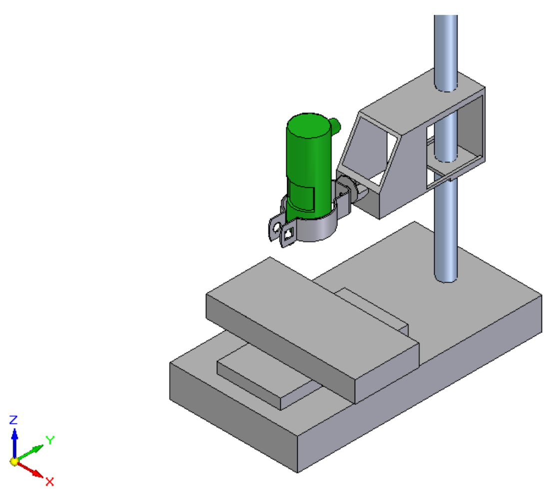
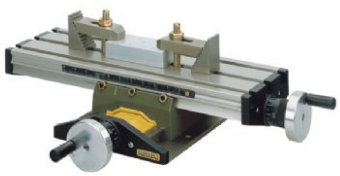


Figure B. 8 Microscope Frame Assembly

Table B.5

Frame and Microscope Parts

Item	Description
Drill Press Motor Stand 	Base, boom, and mount. Proxxon Micro Drill Stand (MB140/S) ($48.00) • Table Size – 4-3/4” x 8-5/8” (120 x 220mm) • Throat Capacity – 5-1/2” (140mm) • Travel 1-3/16” (30mm) • Height (Top of Table to bottom of head) – 7-1/2 (190mm) • Weight – 4 lbs (453g)
Compound Table 	Compound Table that serves at the base for the lower illumination and staging platform. Proxxon Compound Table (KT70) ($96.99) • Work Table: 7 7/8” x 2 ¾” (200 mm x 70 mm) • Adjustment travel in X direction: 5 9/32” (134 mm) • Adjustment travel in Y direction: 1 13/16” (46 mm) • Weight: 1.65 lb (750 g) • 3 T-slots in size 15/32” x 15/64” x 13/64” (12 x 6 x 5 mm), distance between grooves (center-to-center): 63/64” (25 mm) •
USB Microscope 	USB microscope Celestron USB microscope (44302) ($40) • Digital microscope • 10X – 40X and 150X • Max image size 1280 x 1024
#3 Conduit Hanger 	The conduit hanger is used to hold the USB microscope, upper illumination and an external point lamp (optional). #3 Conduit Hanger ($1.99)
3” C-Clamp 	Used for fine adjustments of the microscope height 3” C-Clamp ($2.99)

Upper Illumination Spherical Diffusion Assembly

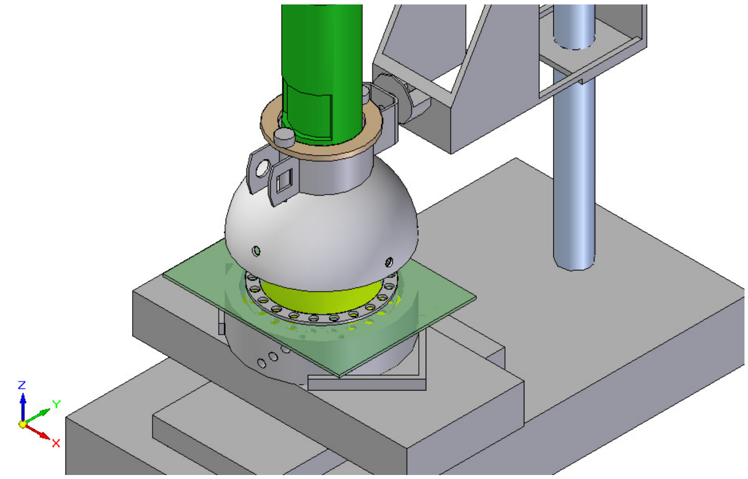


Figure B. 9 Upper Illumination Spherical Diffusion Assembly

Table B.6

Upper Illumination

Item	Description
3” PVC Drain End Cap (Direct illumination and Ring) 	Holds the LED ring light, 3” Schedule 40 PVC drain Cap ($1.05)
2- #10-32 Allen screws	Used to hold illumination assembly to USB microscope
Card Board	Used as washer for Allen screws
Wiffle Ball (Spherical Diffusion) 	Used as spherical diffuser
LED ring light 	70mm automotive 21-LED ring light

Lower Illumination (Light Box) Assembly

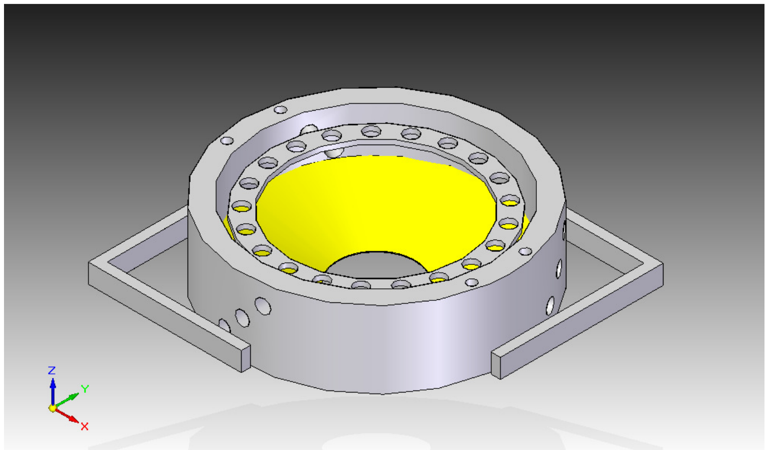


Figure B. 10 Lower Illumination Design without Glass

Table B.7

Lower Illumination

Item	Description
1” length of 3” ID Schedule 40 PVC	Holds LED ring light and condenser assembly
3 - #10-32 Allen screw	To hold led ring light inside fixture
3.5x4.5 glass	Platform on which the objects to be examined are placed.
LED ring light	70mm automotive 21-LED ring light
	
2” Angle Iron	Brackets to position and hold the light box to the stage.
Card Stock	Assorted card stock for illumination experiments.

Glass Stage

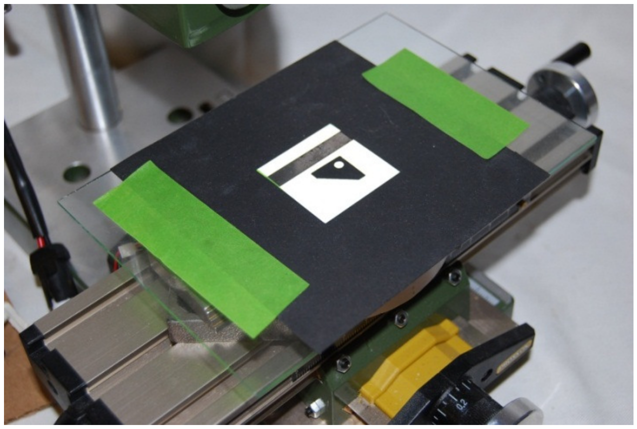


Figure B.11 Glass Stage Set Up for Backlighting a Thin Part

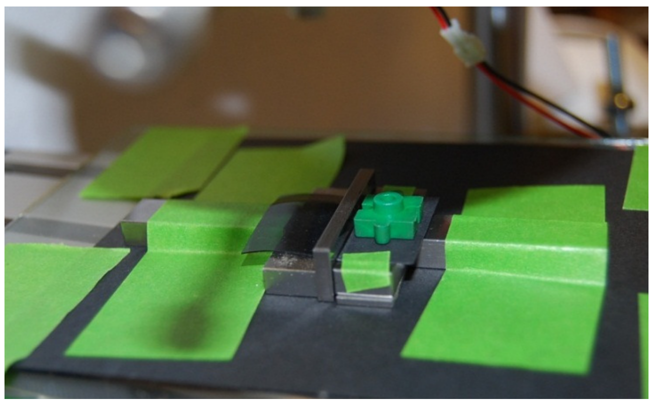


Figure B.16 Glass Stage Set Up using Gage Blocks in Order to Measure a Thick Part.

Table B.7

Glass Stage

Item	Description
3.5x4.5 glass	Platform on which the objects to be examined are placed.
Card Stock	Assorted card stock for illumination experiments.
Translucent Vellum or Wax Paper	Used to diffuse the lower illumination
Green masking tape	Used to tape the card stock, vellum or wax paper to the glass plate. Also to hold the gage blocks in place, if necessary.
Gage Blocks	A set of gage blocks is use to raise the object being examined or the reference target so that they are on the same plane.

Power Panel Assembly

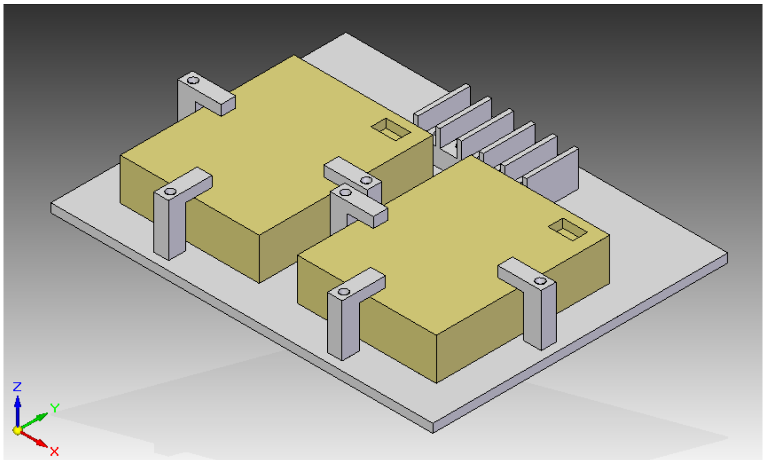
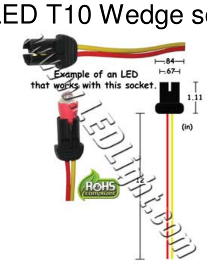


Figure B. 12 Power Supply Panel

Table B.8

Electrical Parts

Item	Description
Battery Holders 	Power Supply. Radio Shack Model 27-411 4-AAA Enclosed Battery Holders
AAA Batteries	8 batteries for 12VDC
4-Gang Terminal strips 	Connect battery holders to T10 Wedge Sockets
2- LED T10 Wedge socket  	Used to connect LED ring lights to the Battery holders.
Card Board	Used as a backing to hold electrical components in place.
Wire Twist Ties	To mount battery packs and terminal blocks,

ALTERNATE CONSTRUCTION METHODS

In the process of researching and designing the noncontact measurement tool for this thesis, a number of alternate hardware was tested. Appendix D provides pro and con information that might be valuable when modifying the tool.

Cross Slide Vise. Cross slide vises (See Figure B.18), commonly used with manual drill press stations, have adjustable lead screws in the x and y directions. These are most commonly used at manual drill press stations. Cross slide vises are less costly than milling tables and have very coarse adjustments. The bases of some power drill stands are designed to accept these vises so they are an acceptable alternate to the more expensive milling table.

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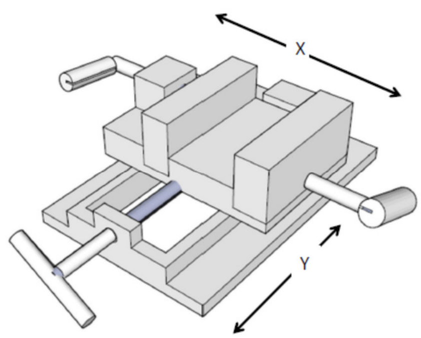


Figure B.13 Cross Slide Vise

Pros

- Low cost. Can be found at discount tool and woodworking equipment stores.

Cons

- Cross-slides have coarse adjustments
- May be difficult to maintain the proper perpendicularity to the microscope.
- Locking mechanisms may not work well.
- Heavy and bulky.

Articulated Vacuum Vise. An articulated vacuum vises (see Figure B.19) uses a vacuum base to lock it to any smooth surface. The vise can be rotated 360-degrees and can be set at any angle.

Figure B.14 Articulated Vacuum Vise

Pros

- This vise was found to work great when using LED night lights for backlighting objects.
- Good for holding fixtures or parts with angled faces at the proper orientation. An indicator is needed to make sure the object is perpendicular with the microscope.

Cons

- Can be difficult to set up.
- May be too high to use with a power drill press fixture, but works well with a height gage.

Microscope Stand. Several off-the-shelf stands were considered for the microscope. The Power drill support stand appeared to be the most suitable, with the vertical height gage coming in second. Other stands included the Port-A-Line and an indicator stand. Honorable mention goes to Giorgio Carboni (Carboni, 2001) for his stereo microscope fabrication write-up,

ALTERNATE CALIBRATION FIXTURES

Drafter's Circle Template. Drafter's circle templates (see Figure B.20) are designed for accurate circle representations on blueprints. The circles are transferred to paper or vellum by holding a standard drafting pencil or ink pen against the edge of the cut out circle in the template. The template circles are approximately .020" larger to make room for the pencil or pen. Drafter's circle templates are available in non-glare green plastic. They are available in English and Metric dimensions.

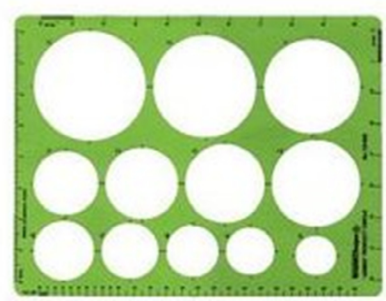


Figure B.15 Drafter's Template

Pros

- The hole sizes in the templates are amazingly accurate.
- Can be used if objects being measured are on a large flat surface. This is not a problem if the microscope is on a boom-style fixture.

Cons

- The templates are large and unwieldy.
- Cutting the template can lead to permanent warpage or bending which makes them unusable.

Gage Blocks. Gage blocks (Figure B.21) are used to calibrate other measurement equipment. In this case, they can be used to generate an accurate distance in an image for calibration or put a reference target and part surface on the same plane.

Figure B.21 Gage Blocks

Pros

- Can be used to set calipers and micrometers to accurate distances for reference in images.
- Gage blocks can be used to set the distance accurately in the image, but require a surface as the same height at the block to get a good image.

Cons

- Gage blocks have edge relief that might make it difficult to pick out the real edge in the image.

Line Graduated Measuring Instruments. Other calibration methods tested used line graduated measuring instruments such as engineering scales, micrometers, and calipers. Engineering scales ave fixed gradients and, when included in the microscope image, offer a secondary measurement approximation. Micrometers and calipers can be set up using calibrated gage blocks to guarantee correctness.

Calipers and Micrometers. Calipers and Micrometers are designed to be calibrated. Calibrated calipers and micrometers can be used to provide accurate calibration scaling in images.

Pros

- Properly calibrated calipers and micrometers can be used to provide measurement information needed to calibrate the image in AutoCad.

Cons

- Some calipers and micrometers do not lie flat and need to be supported if used for measurement.
- The object being measured needs to be place in the same plane in relation to the calipers or micrometers. This may be difficult.

Engineering Scale. An engineering scale (see Figure B.22) is an example of a line graduated measuring instrument. These scales come in a variety of sizes and types and are mostly used for reference.

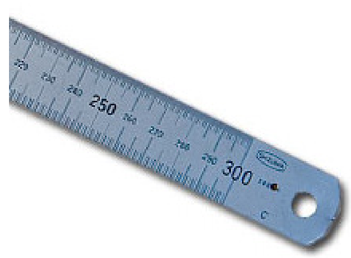


Figure B.22 Example of a Metric Engineering Steel Ruler

Pros

- Scales have been used in microscope views for centuries.

- If the object being measure has a large tolerance (±.010 for example), a scale can be used to calibrate the image.

Cons

- Scales cannot be calibrated accurately so they can only be used for reference.

- If the object being measured has a very small tolerance (±.001 for example), a scale cannot be used.

FINAL DESIGN

The final 2DNCMT design is shown in Figure B.23. It uses the power drill support and matching compound table from Proxxon. In this view, the direct down-facing upper illumination is attached. The blocking ring is on the stage. Upper illumination is turned on. A yellow background is being used to contrast a thick plastic part. No lower illumination is being used. On the left is the battery operated power supply for the LEDs. Off to the right is a long handled Allen wrench, the C-clamp used for fine adjustment, and the spherical cover used for indirect illumination.

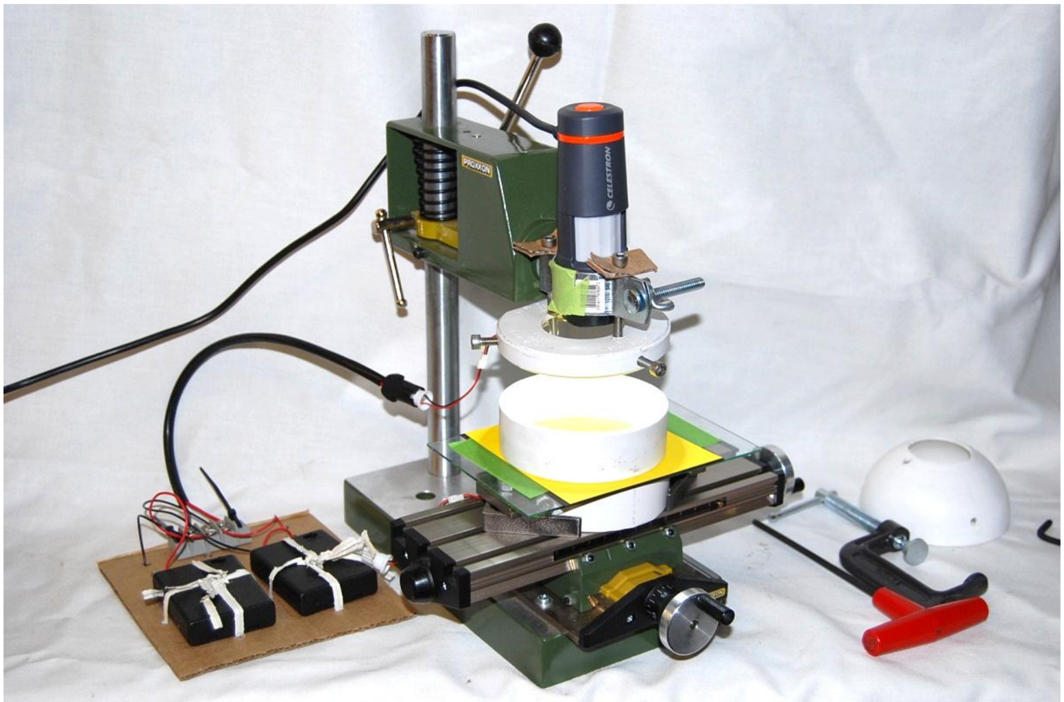


Figure B.16 Final 2DNCMT Design with Direct Illumination Cover Installed

Alternate Design. An alternate 2DNCMT design is shown in Figure B.24. This design used an LED night light for lower illumination. The nightlight is held in place with an articulating vise. The USB microscope support is a vertical height gage with a #3 conduit hanger to hold the microscope. This design has a custom bracket (visible in right image in Figure B.17) for the conduit hanger that required metal cutting and welding. The upper illumination used in the final design can be used on this design.

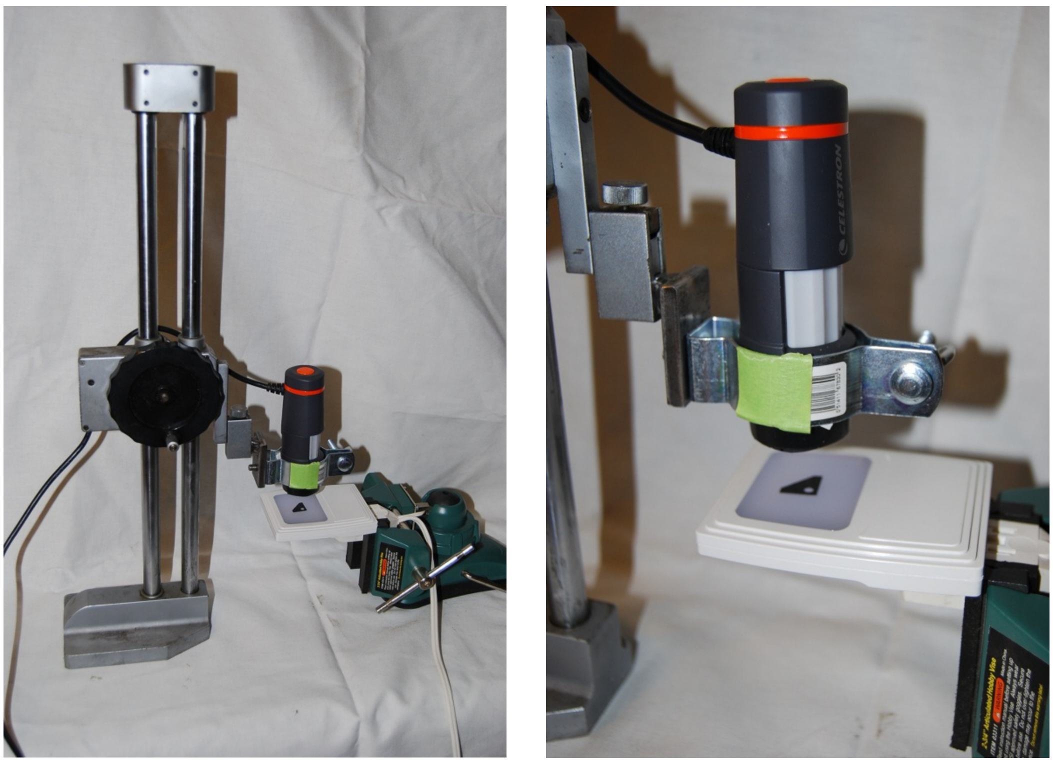


Figure B. 17 Alternative 2DNCMT Configuration
Left: The Complete Design, Right: A Close Up of the USB Microscope and Lower Illumination (LED Night Light)

APPENDIX C

DESIGN DATA

This appendix provides information for parts designed and fabricated for this project. All of these parts may be made with common household tools. Any exceptions are noted. In this section, the following designs are described:

- Reference Targets
- Squares and Dots Reference Target Plate
- Upper Illumination Fixtures
    - Upper Illumination Simple Enclosure
    - UV ring light & Enclosure
    - Spherical Cover
- Lower Illumination Fixtures
    - Lower Illumination Simple Enclosure
    - Stage
- Upper and Lower Illumination Power Supply Modules

TARGET RINGS

Target rings can be precision machined, but flat washers that have been measured and qualified using some other measurement tool work just as good.

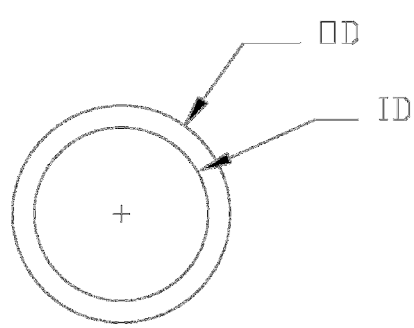


Figure C.1 Target Ring Drawing

DOTS AND SQUARES

A detailed dimensioned drawing of a squares and dots strip is provided. These strips were used early in the project but replaced by ring targets and feeler gages.

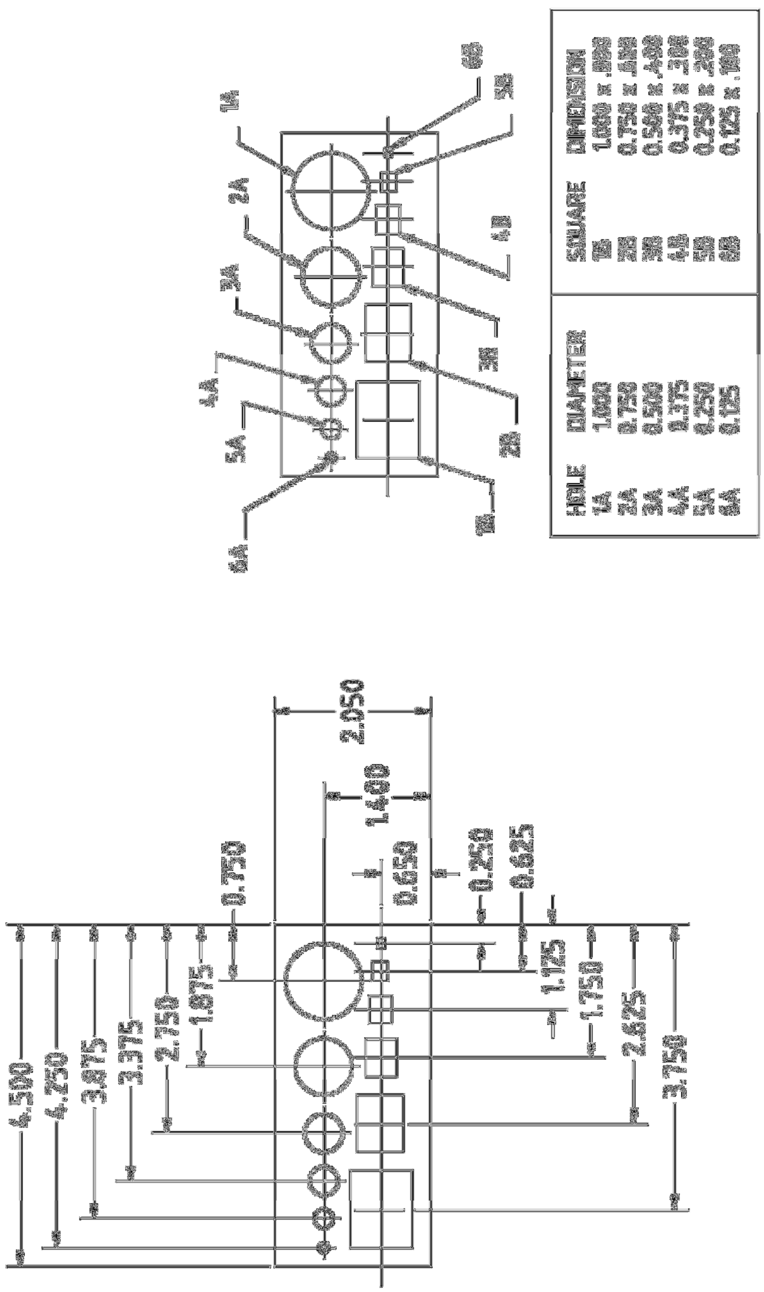


Figure C.2 Dimensioned Drawing of a Dots and Squares Slide

UPPER ILLUMINATION DESIGN

The upper illumination design as shown in C.3 holds a LED ring light.

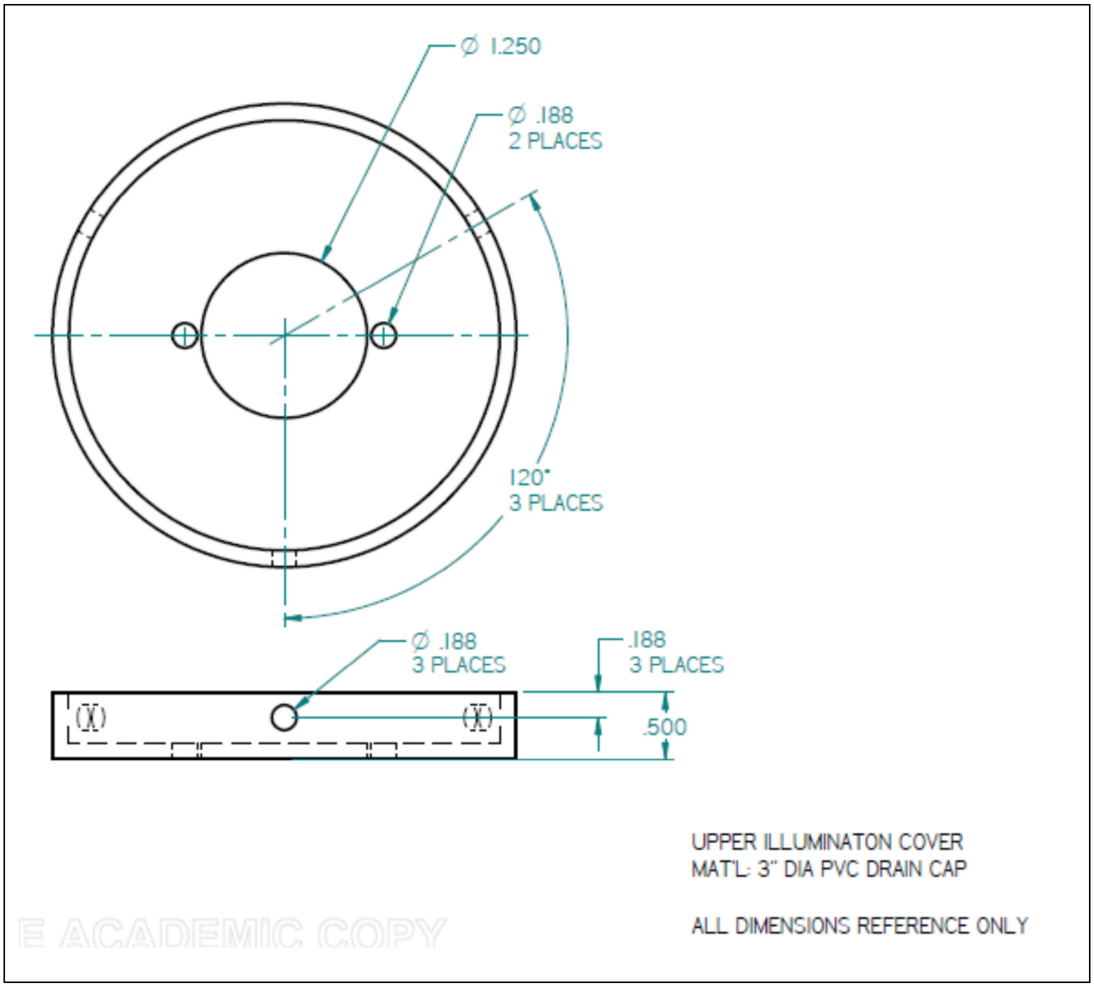


Figure C.3 Dimensioned Drawing of the Upper Illumination Cover

LIGHT BOX DESIGN

The lower illumination as shown in Figure C.4 holds the LED ring light and provides a place for the stage (a 3” x 4” piece of glass) to rest.

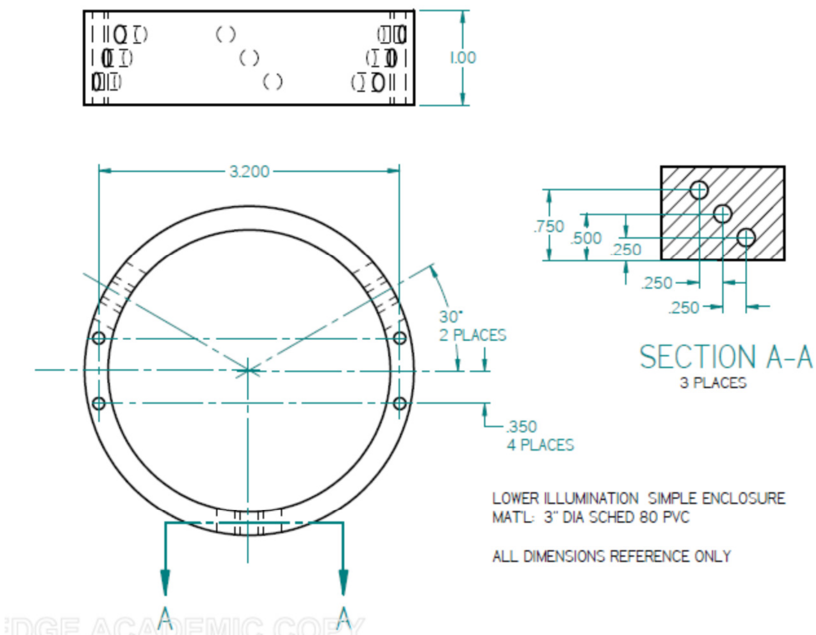


Figure C.4 Dimensioned Drawing of the Lower Illumination Fixture

SPHERICAL DIFFUSER COVER

The example spherical diffuser cover was made from a 3 ” dia hollow ball. Another choice would be a small stainless steel mixing bowl.   Figure C.5 shows a Solid Edge model of the completed spherical diffuser cover. Figure C.6 is its CAD drawing.

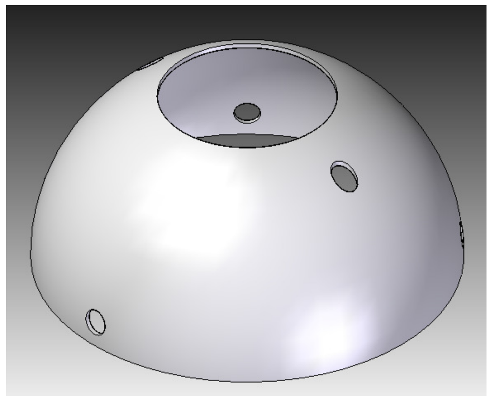


Figure C.5 Isometric View of the Spherical Diffuser Cover in Solid Edge

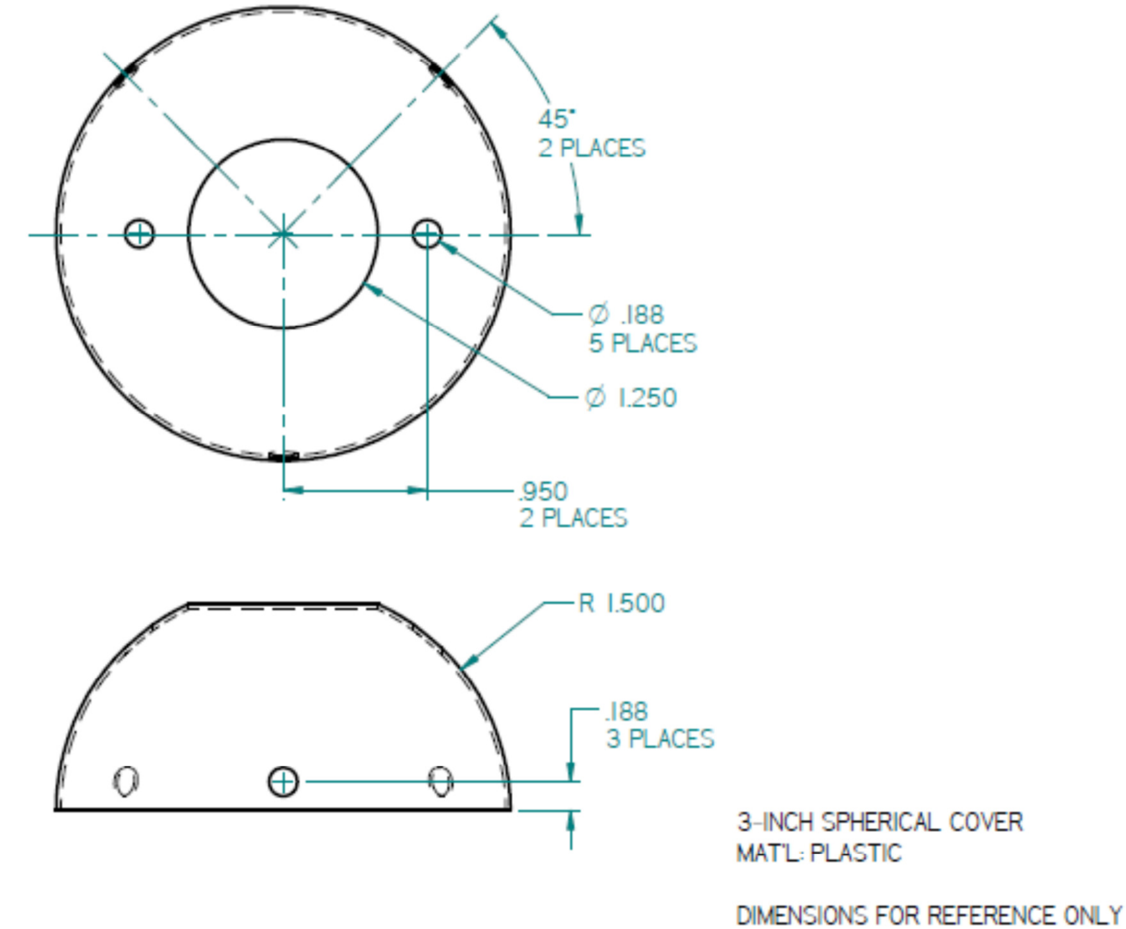


Figure C.6 Dimensioned Drawing of the Spherical Diffuser Cover

UPPER AND LOWER ILLUMINATION POWER SUPPLY MODULES

Any material can be used for the holding the power supply components. For this project, cardboard squares and wire twist ties were used as prototype. To make it less cumbersome, the upper and lower illumination fixtures each have their own power supply modules. Figure C.7 shows the battery boxes clamped down to a sturdy backing.

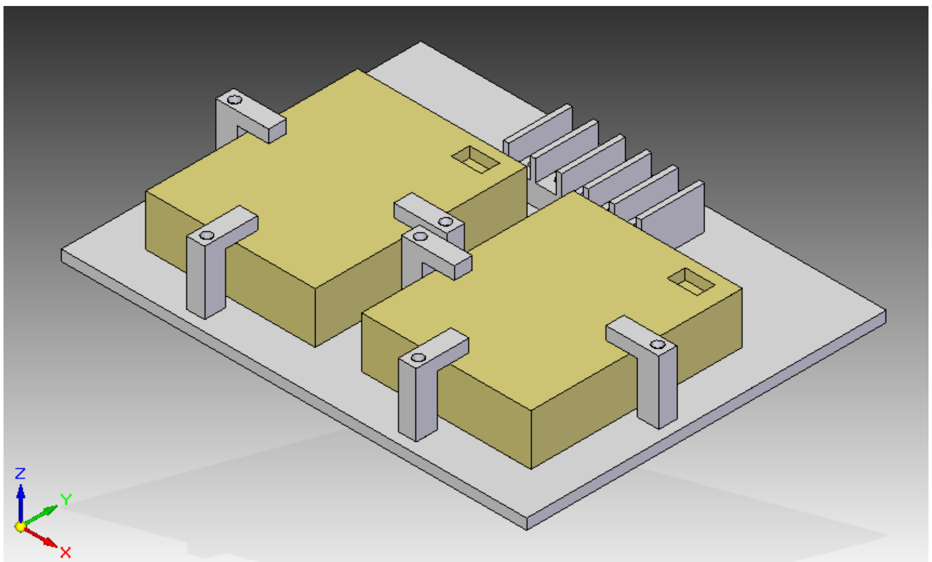


Figure C.7 Solid Edge 3D Model of the Power Supply Module

PAPER CONE FOR LOWER ILLUMINATION

The paper cone (see Figure C.8) was added later the lower illumination light box to reflect the light toward the center of the stage. This was made from paper using the following pattern.

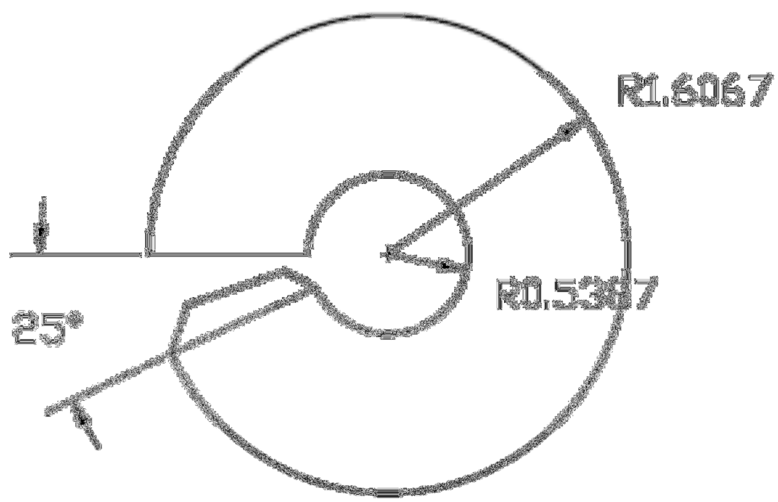


Figure C.8 Pattern Used for the Reflective Cone used in the Light Box

DIFFUSION FILTER

The diffusion filter was precisely designed and fabricated for this project. It was made from 65# card stock. A CNC paper cutter was used to cut it out. While the diffusion filter shown in Figures C.9 and C.10 is not to scale it can be used as an example for experimentation.

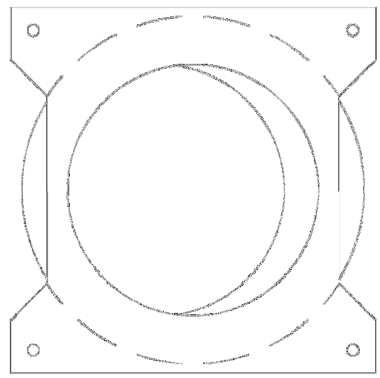


Figure C.9 Assembled view of the diffusion filter

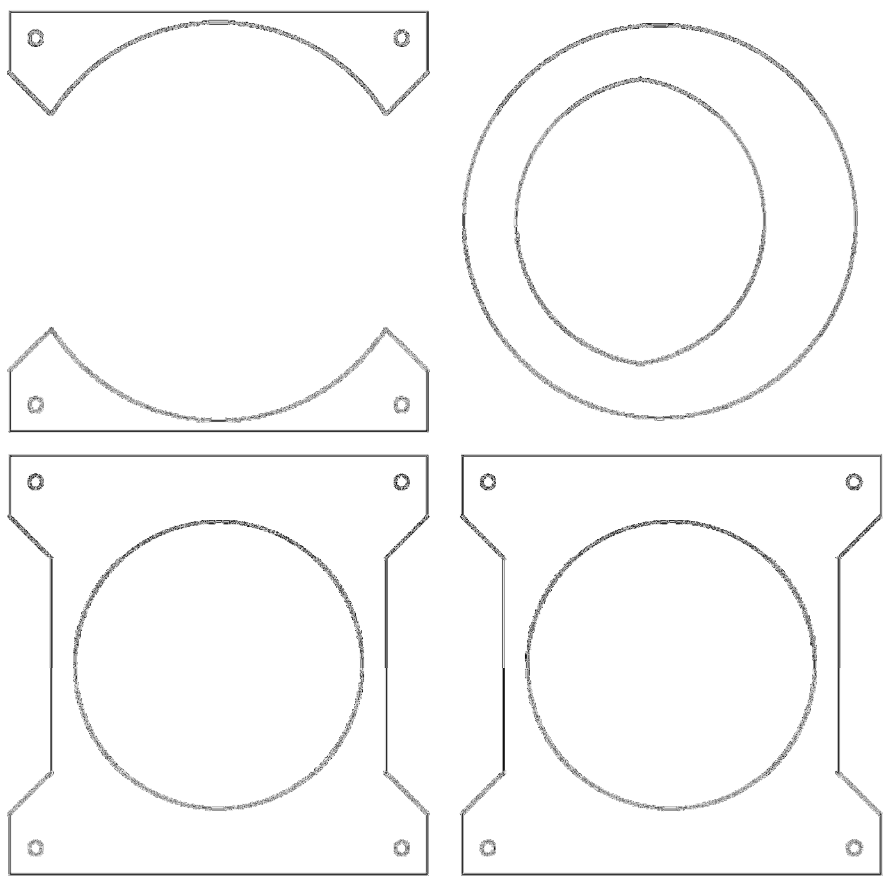


Figure C.10 Unassembled View of the Diffusion Filter

SLIDE APERTURE

The slide aperture was precisely designed and fabricated for this project. It was made from 65# card stock. A CNC paper cutter was used to cut it out. While the diffusion filter shown in Figure C.11 is not to scale it can be used as an example for experimentation.

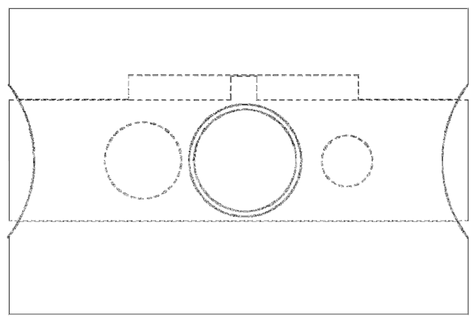


Figure C.11 Assembled View of the Slide Aperture

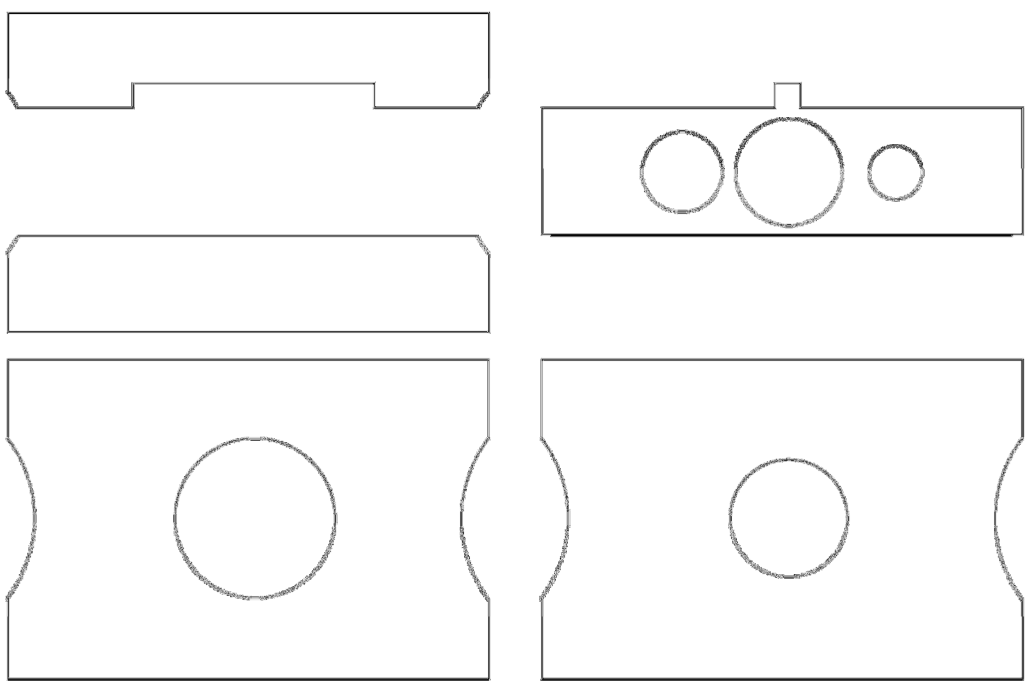


Figure C.12 Unassembled View of the Slide Aperture

APPENDIX D

TEST DATA AND RESULTS

This appendix contains the drawings, Gage R&R data and results for the following gage tests:

- 2DNCMT and Nikon VMA-2520 Comparison
- Large Paper Part
- Small Paper Part
- Micro Part

The following tests were performed for the 2DNCMT – Nikon Comparison Test:

- Gage R&R Studies

The following tests were performed on large paper, small paper, and micro parts:

- Measurement Uncertainty Test
- Process Capability Test
- Gage R&R Studies

TEST DESCRIPTIONS

The following tests are described in this section:

- Measurement Uncertainty Test
- Process Capability Test
- Gage R&R Studies

Measurement Uncertainty. The Inter-Laboratory Comparison Test is a proficiency test used to demonstrate confidence. It also works well for performing measurement uncertainty testing. Refer to The Metrology Handbook (Bucher, 2004) and its accompanying CD or ISO Guide 43-1 for more information.

Process Capability Calculations

Refer to Quality Control, 8th ed., (Besterfield, 2009) or any other quality book on Statistical Quality Control for information on how to perform and analyze a Process Capability Test.

Honest Gage GRR and ICC Calculations. The Honest Gage R&R calculations use the values found in the VarComp field in the top table in the Minitab results. The numbers highlighted in yellow in Figure D.1 are the Honest Gage R&R study results for the Combined Gage R&R (CRR) and Intraclass Correlation Coefficient (ICC). The CRR and ICC values are used to determine the monitor class of the gage.

HONEST GAGE R&R RESULTS

Source	VarComp		%Contribution (of VarComp)
Total Gage R&R	0.0000182	**(CRR)**	87.40
Repeatability	0.0000174		83.54
Reproducibility	0.0000008		3.85
Part-To-Part	0.0000026	**(ICC)**	12.60
Total Variation	0.0000208	**(HTV)**	100.00

Figure D.1 Example of Minitab Gage R&R Results for the Honest Combined Gage R&R (CRR) and the Intraclass Correlation Coefficient (ICC)
Note: The values highlighted in yellow are used to calculate CRR and ICC.

Equations

$$CRR = 100 * (GRR / TV) \quad (1)$$

$$ICC = 100 * (PV / TV) \quad (2)$$

Notes:

1. The Honest Gage R&R values can be obtained using Minitab. Use the Gage R&R (crossed) with the Xbar and R option.

2. Minitab rounds off values. If the values in the Var Comp column are too small to use, then use equations 1, 2, and 3 to calculate to calculate CRR and ICC. Otherwise, use the values from the VarComp column directly to calculate CRR and ICC.

DATA AND TEST RESULTS FOR THE 2DNCMT-NIKON COMPARISON TEST

Table D.0.1

Nikon Comparison Data for the 2DNCMT-Nikon Comparison Test

Nikon Comparison Data 2 op, 2 trials, 5 parts

StdOrder	RunOrder	Parts	Operators	X	Y
1	1	1	1	0.36195	0.36064
2	2	1	2	0.36733	0.37041
3	3	2	1	0.36362	0.36600
4	4	2	2	0.37061	0.37636
5	5	3	1	0.36451	0.36458
6	6	3	2	0.36813	0.36656
7	7	4	1	0.36221	0.36117
8	8	4	2	0.36891	0.36824
9	9	5	1	0.36136	0.36237
10	10	5	2	0.36900	0.37114
11	11	1	1	0.36320	0.36484
12	12	1	2	0.36725	0.36927
13	13	2	1	0.36243	0.36206
14	14	2	2	0.37143	0.37063
15	15	3	1	0.36418	0.36245
16	16	3	2	0.36726	0.36762
17	17	4	1	0.36770	0.36268
18	18	4	2	0.36809	0.37054
19	19	5	1	0.36438	0.36188
20	20	5	2	0.36976	0.36910

Table D..2

2DNCMT Comparison Data for the 2DNCMT-Nikon Comparison Test

2DNCMT Comparison Data 2 op, 2 trials, 5 parts

StdOrder	RunOrder	Parts	Operators	X	Y
1	1	1	1	0.37905	0.37855
2	2	1	2	0.37636	0.37470
3	3	2	1	0.37415	0.37572
4	4	2	2	0.37382	0.37403
5	5	3	1	0.37541	0.37497
6	6	3	2	0.37874	0.37460
7	7	4	1	0.37353	0.37103
8	8	4	2	0.37443	0.37273
9	9	5	1	0.37538	0.37435
10	10	5	2	0.37461	0.37467
11	11	1	1	0.37689	0.37558
12	12	1	2	0.37319	0.37339
13	13	2	1	0.36446	0.36745
14	14	2	2	0.37247	0.37546
15	15	3	1	0.37228	0.36907
16	16	3	2	0.36879	0.36958
17	17	4	1	0.37140	0.37005
18	18	4	2	0.37712	0.37349
19	19	5	1	0.36302	0.36320
20	20	5	2	0.37402	0.37464

Table D.3

Plastic Part Measured with Dial Calipers

Part #	X	Y
1	0.370	0.370
2	0.367	0.368
3	0.368	0.370
4	0.366	0.368
5	0.369	0.368
6	0.365	0.369
7	0.368	0.369
8	0.368	0.372
9	0.366	0.370
10	0.367	0.369
Range	0.005	0.004
Mean	0.367	0.369
Standard Deviation	0.002	0.001

AIAG Gage R&R Results for 2DNCMT X Dimension

Gage R&R for X

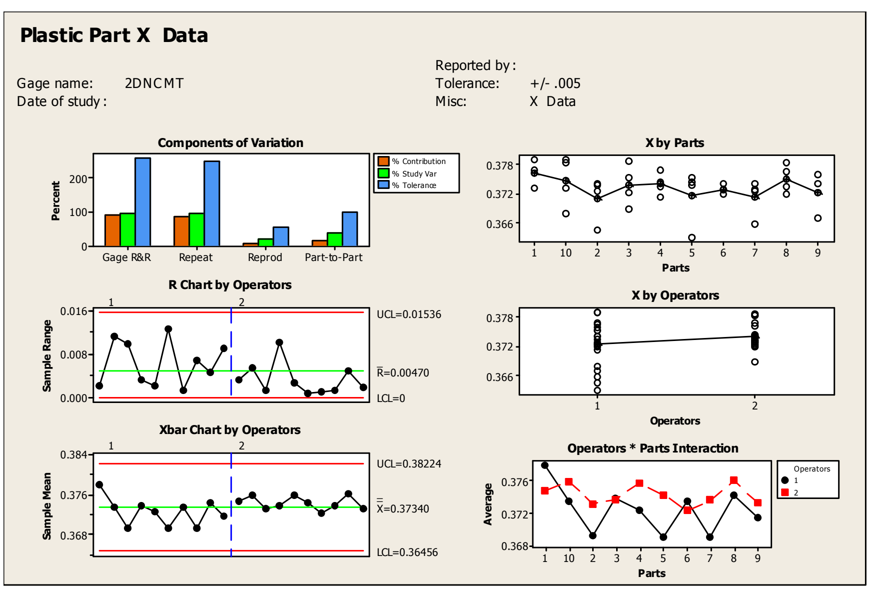
Gage name: 2DNCMT
Date of study:
Reported by:
Tolerance: +/- .005
Misc: X Data

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000182	87.40
Repeatability	0.0000174	83.54
Reproducibility	0.0000008	3.85
Part-To-Part	0.0000026	12.60
Total Variation	0.0000208	100.00

Process tolerance = 0.01

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.0042626	0.0255757	93.49	255.76
Repeatability	0.0041676	0.0250053	91.40	250.05
Reproducibility	0.0008952	0.0053711	19.63	53.71
Part-To-Part	0.0016187	0.0097123	35.50	97.12
Total Variation	0.0045596	0.0273577	100.00	273.58

Number of Distinct Categories = 1



AIAG Gage R&R Results for 2DNCMT Y Dimension

Gage R&R for Y

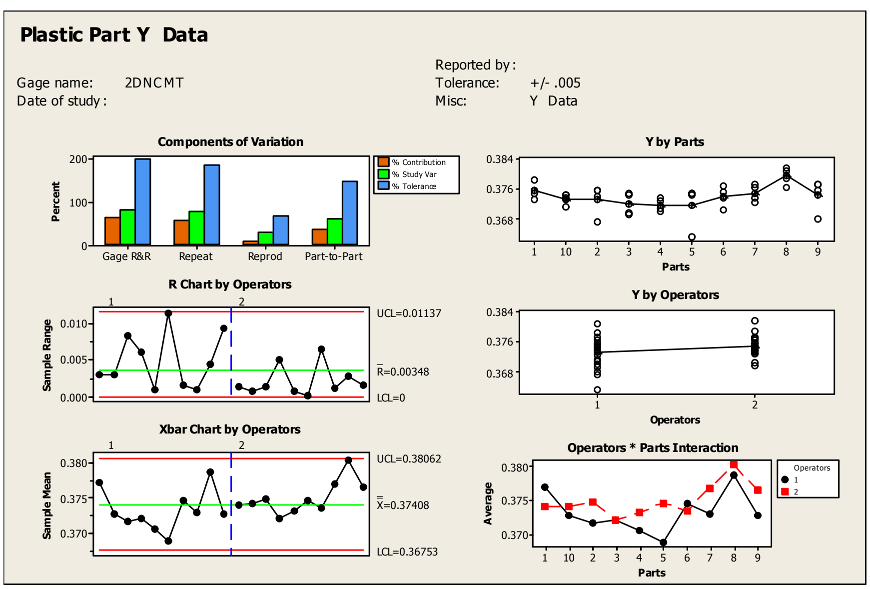
Gage name: 2DNCMT
Date of study:
Reported by:
Tolerance: +/- .005
Misc: Y Data

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000107	64.12
Repeatability	0.0000095	56.88
Reproducibility	0.0000012	7.24
Part-To-Part	0.0000060	35.88
Total Variation	0.0000167	100.00

Process tolerance = 0.01

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.0032747	0.0196482	80.07	196.48
Repeatability	0.0030844	0.0185061	75.42	185.06
Reproducibility	0.0011002	0.0066010	26.90	66.01
Part-To-Part	0.0024497	0.0146981	59.90	146.98
Total Variation	0.0040896	0.0245374	100.00	245.37

Number of Distinct Categories = 1



AIAG Gage R&R Results for Nikon VMA-2520 X Dimension

Gage R&R Study - XBar/R Method

Gage R&R for X

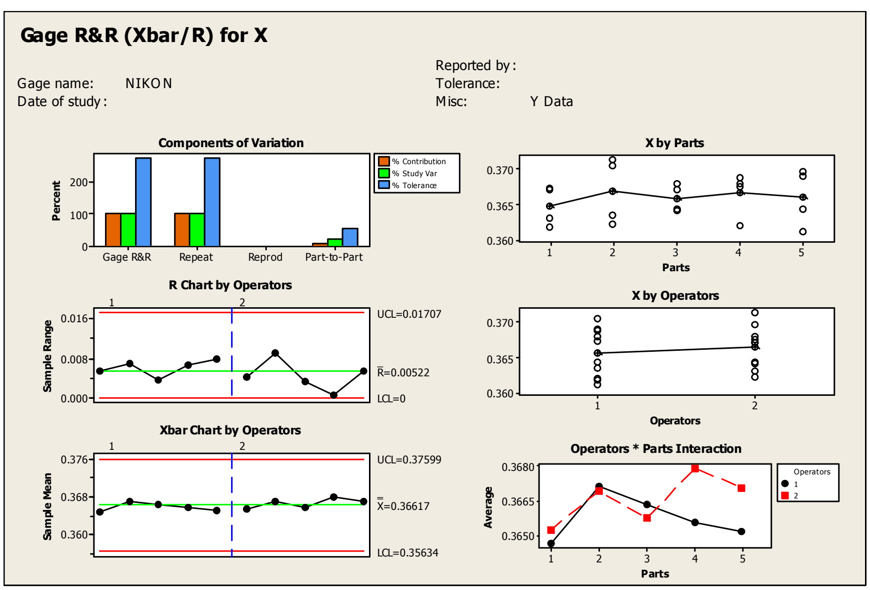
Gage name: Nikon VMS-2520
Date of study: 8/29/2011
Reported by:
Tolerance: +/0 .005
Misc: Plastic Part X Dimension

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000203	96.62
Repeatability	0.0000203	96.62
Reproducibility	0.0000000	0.00
Part-To-Part	0.0000007	3.38
Total Variation	0.0000210	100.00

Process tolerance = 0.01

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.0045026	0.0270155	98.29	270.16
Repeatability	0.0045026	0.0270155	98.29	270.16
Reproducibility	0.0000000	0.0000000	0.00	0.00
Part-To-Part	0.0008427	0.0050565	18.40	50.56
Total Variation	0.0045808	0.0274846	100.00	274.85

Number of Distinct Categories = 1



AIAG Gage R&R Results for Nikon VMA-2520 Y Dimension

Gage R&R Study - XBar/R Method

Gage R&R for Y

Gage name:	NIKON VMS-2520
Date of study:	
Reported by:	
Tolerance:	+/-.005
Misc:	Plastic Part Y Dimension

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000377	95.09
Repeatability	0.0000377	95.09
Reproducibility	0.0000000	0.00
Part-To-Part	0.0000019	4.91
Total Variation	0.0000396	100.00

Process tolerance = 0.01

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.0061379	0.0368276	97.51	368.28
Repeatability	0.0061379	0.0368276	97.51	368.28
Reproducibility	0.0000000	0.0000000	0.00	0.00
Part-To-Part	0.0013952	0.0083710	22.16	83.71
Total Variation	0.0062945	0.0377670	100.00	377.67

Number of Distinct Categories = 1

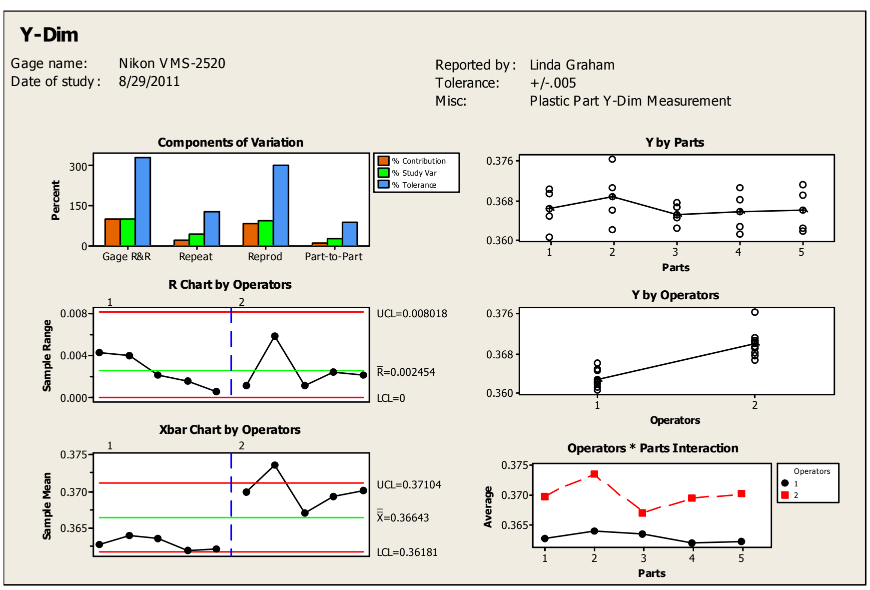


Table D.0.4

Honest Gage R&R CRR and ICC Results for the Nikon Test

Honest Gage R&R Results	X Dimension Value	Y Dimension Value
CRR	87.5	64.07
ICC	12.5	35.93
Monitor Class	4 – Don't Use	3 - Acceptable

Table D.0.5

Honest Gage R&R CRR and ICC Results for the 2DNCMT Test

Honest Gage R&R Results	X Dimension Value	Y Dimension Value
CRR	95.60	93.65
ICC	4.40	6.03
Monitor Class	4 – Don't Use	4 – Don't Use

GAGE R&R STUDY DATA AND MINITAB RESULTS FOR THE LARGE PAPER PART

This section contains the following information related to the large paper part.

- Dimensioned Drawing
- Gage R&R Data
- AIAG Gage R&R results (Minitab Format) for each dimension measured.
- Honest Gage R&R results (Excel Format) for each dimension measured.
- CAD Overlay Examples showing the accuracy of the 2DNCMT.

Dimensioned Drawing of Large Paper Part. A dimensioned drawing of the large paper part is shown in Figure D.2.

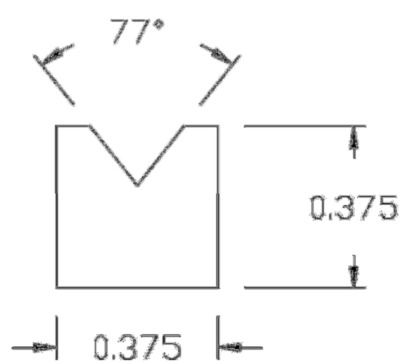


Figure D.2 Dimensioned Drawing of the Large Paper Part

GAGE R&R Data for the Large Paper Part

Table D.5

Gage R&R Data for Large Paper Part

StdOrder	RunOrder	Parts	Operators	X	Y	A
1	1	1	1	0.37510	0.37593	76.60979
2	2	1	2	0.37233	0.37867	74.37050
3	3	1	3	0.37361	0.37384	76.80064
4	4	2	1	0.37838	0.37791	76.10609
5	5	2	2	0.37570	0.37479	75.09241
6	6	2	3	0.37967	0.37823	76.41139
7	7	3	1	0.37529	0.37340	75.90718
8	8	3	2	0.37142	0.37270	76.16518
9	9	3	3	0.37538	0.37408	75.86975
10	10	4	1	0.37255	0.37409	77.12264
11	11	4	2	0.37363	0.37564	76.78271
12	12	4	3	0.37357	0.37512	76.36032
13	13	5	1	0.37391	0.37474	75.00563
14	14	5	2	0.37342	0.37211	75.78139
15	15	5	3	0.37331	0.37858	74.10515
16	16	6	1	0.37437	0.37401	77.54783
17	17	6	2	0.37407	0.37338	76.37699
18	18	6	3	0.37815	0.37833	76.73780
19	19	7	1	0.37431	0.37441	74.44439
20	20	7	2	0.37696	0.37709	74.40227
21	21	7	3	0.37464	0.37642	77.08609
22	22	8	1	0.37237	0.37787	76.53851
23	23	8	2	0.37431	0.37126	76.21474
24	24	8	3	0.37212	0.37653	76.56201
25	25	9	1	0.37366	0.37131	75.83974
26	26	9	2	0.37632	0.37471	76.05384
27	27	9	3	0.37087	0.37634	76.68921
28	28	10	1	0.37140	0.37159	76.57765
29	29	10	2	0.37697	0.37572	76.06345
30	30	10	3	0.37568	0.37619	77.30157
31	31	1	1	0.37255	0.37587	74.19213
32	32	1	2	0.37326	0.37552	76.43072
33	33	1	3	0.37414	0.37483	77.01106
34	34	2	1	0.37510	0.37798	75.71709
35	35	2	2	0.37688	0.37756	77.34260
36	36	2	3	0.38018	0.37874	76.02542
37	37	3	1	0.37431	0.37707	75.21196
38	38	3	2	0.37165	0.37708	77.02476
39	39	3	3	0.37536	0.37455	76.06743
40	40	4	1	0.37237	0.37570	76.90372
41	41	4	2	0.37469	0.37637	76.06202
42	42	4	3	0.37359	0.37582	76.98131

StdOrder	RunOrder	Parts	Operators	X	Y	A
43	43	5	1	0.37529	0.37561	75.99273
44	44	5	2	0.37727	0.37537	76.21550
45	45	5	3	0.37233	0.37815	74.49339
46	46	6	1	0.37140	0.37391	76.23964
47	47	6	2	0.37827	0.37614	75.42715
48	48	6	3	0.37517	0.37685	75.68337
49	49	7	1	0.37437	0.37410	76.14118
50	50	7	2	0.37873	0.37796	75.11266
51	51	7	3	0.37205	0.37813	74.51484
52	52	8	1	0.37391	0.37917	74.71845
53	53	8	2	0.37420	0.37453	76.89203
54	54	8	3	0.37361	0.37907	76.84272
55	55	9	1	0.37838	0.37730	77.23808
56	56	9	2	0.37631	0.37517	75.64300
57	57	9	3	0.37572	0.37310	76.10068
58	58	10	1	0.37366	0.37878	76.17390
59	59	10	2	0.37974	0.37648	76.08704
60	60	10	3	0.37507	0.37461	77.07797

Process Capability Results for the Large Paper Part

Table D.6

Process Capability Results for the Large Paper Part X Dimension

Part	A	B	C	D	E	F		Xbar	Range
1	0.375	0.373	0.372	0.373	0.374	0.374		0.373	0.003
2	0.378	0.375	0.376	0.377	0.380	0.380		0.378	0.005
3	0.375	0.374	0.371	0.372	0.375	0.375		0.374	0.004
4	0.373	0.372	0.374	0.375	0.374	0.374		0.373	0.002
5	0.374	0.375	0.373	0.377	0.373	0.372		0.374	0.005
6	0.374	0.371	0.374	0.378	0.378	0.375		0.375	0.007
7	0.374	0.374	0.375	0.372	0.377	0.379		0.375	0.007
8	0.372	0.374	0.374	0.374	0.372	0.374		0.373	0.002
9	0.374	0.378	0.371	0.376	0.376	0.376		0.375	0.008
10	0.371	0.374	0.377	0.380	0.376	0.375		0.375	0.008
						Sum		3.747	0.051
	nominal	tolerance							
	0.375	0.007						Xbar =	0.375
								Rbar =	0.005
								Sigma =	0.002
								6-Sigma =	0.012
								USL =	0.382
								LSL =	0.368
								Cp =	1.167
								CpU =	1.214
								CpL =	1.120
								Cpk =	1.120

Table D.7

Process Capability Results for the Large Paper Part Y Dimension

Part	A	B	C	D	E	F	Xbar	Range
1	0.376	0.376	0.379	0.376	0.374	0.375	0.376	0.005
2	0.378	0.378	0.375	0.378	0.378	0.379	0.378	0.004
3	0.373	0.377	0.373	0.377	0.374	0.375	0.375	0.004
4	0.374	0.376	0.376	0.376	0.375	0.376	0.375	0.002
5	0.375	0.376	0.372	0.375	0.379	0.378	0.376	0.006
6	0.374	0.374	0.373	0.376	0.378	0.377	0.375	0.005
7	0.374	0.374	0.376	0.378	0.377	0.378	0.376	0.004
8	0.378	0.379	0.371	0.375	0.377	0.379	0.376	0.008
9	0.371	0.377	0.376	0.373	0.375	0.375	0.375	0.006
10	0.372	0.379	0.376	0.376	0.376	0.375	0.376	0.007
						Sum	3.758	0.052

nominal	tolerance
0.375	0.007

Xbar =	0.376
Rbar =	0.005
Sigma =	0.002
6-Sigma =	0.012
USL =	0.382
LSL =	0.368
Cp =	1.167
CpU =	1.038
CpL =	1.296
Cpk =	1.038

Table D.8

Process Capability Results for the Large Paper Part A Dimension

Part	A	B	C	D	E	F	Xbar	Range
1	76.610	74.192	74.371	76.431	76.801	77.011	75.927	2.430
2	76.106	75.717	75.092	77.343	76.411	76.025	75.870	1.319
3	75.907	75.212	76.165	77.025	75.870	76.067	75.981	0.295
4	77.123	76.904	76.783	76.062	76.360	76.981	76.755	0.762
5	75.006	75.993	75.781	76.216	74.105	74.493	74.964	1.676
6	77.548	76.240	76.377	75.427	76.738	75.683	76.888	1.171
7	74.444	76.141	77.086	74.515	74.402	75.113	75.311	2.684
8	76.539	74.718	76.215	76.892	76.562	76.843	76.438	0.347
9	75.840	77.238	76.689	76.101	76.054	75.643	76.194	0.849
10	76.578	76.174	76.063	76.087	77.302	77.078	76.648	1.238
						Sum	760.976	12.773

nominal	tolerance
76.500	2

Xbar =	76.098
Rbar =	1.277
Sigma =	0.504
6-Sigma =	3.024
USL =	78.500
LSL =	74.500
Cp =	1.323
CpU =	1.589
CpL =	1.056
Cpk =	1.056

Measurement Uncertainty Results for the Large Paper Part

Table D.9

Measurement Uncertainty Results for the Large Paper Part X Dimension

Specification of Equipment	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007
Uncertainty of Calibrator (Type B)	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040
Trial	**Part 1**	**Part 2**	**Part 3**	**Part 4**	**Part 5**	**Part 6**	**Part 7**	**Part 8**	**Part 9**	**Part 10**	
A	0.37510	0.37838	0.37529	0.37255	0.37391	0.37437	0.37431	0.37237	0.37366	0.37140	
B	0.37255	0.37510	0.37431	0.37237	0.37529	0.37140	0.37437	0.37391	0.37838	0.37366	
C	0.37233	0.37570	0.37142	0.37363	0.37342	0.37407	0.37464	0.37431	0.37087	0.37697	
D	0.37326	0.37688	0.37165	0.37469	0.37727	0.37827	0.37205	0.37420	0.37572	0.37974	
E	0.37361	0.37967	0.37538	0.37357	0.37331	0.37815	0.37696	0.37212	0.37632	0.37568	Summary
F	0.37414	0.38018	0.37536	0.37359	0.37233	0.37517	0.37873	0.37361	0.37631	0.37507	Statistics
Sum	2.24099	2.26591	2.24341	2.24040	2.24553	2.25143	2.25106	2.24052	2.25126	2.25252	22.48303
Mean	0.37350	0.37765	0.37390	0.37340	0.37426	0.37524	0.37518	0.37342	0.37521	0.37542	0.37472
Maximum Value	0.37510	0.38018	0.37538	0.37469	0.37727	0.37827	0.37873	0.37431	0.37838	0.37974	0.38018
Minimum Value	0.37233	0.37510	0.37142	0.37237	0.37233	0.37140	0.37205	0.37212	0.37087	0.37140	0.37140
Range	0.00277	0.00508	0.00396	0.00232	0.00494	0.00687	0.00668	0.00219	0.00751	0.00834	0.00878
Standard Deviation	0.00103	0.00209	0.00188	0.00084	0.00177	0.00263	0.00234	0.00095	0.00261	0.00285	0.00225
+ 3 Sigma	0.37659	0.38393	0.37954	0.37593	0.37955	0.38312	0.38218	0.37626	0.38303	0.38396	0.38146
- 3 Sigma	0.37041	0.37137	0.36827	0.37087	0.36896	0.36736	0.36817	0.37058	0.36739	0.36688	0.36797
Median	0.37344	0.37763	0.37480	0.37358	0.37367	0.37477	0.37451	0.37376	0.37602	0.37538	0.37423
Uncertainty (Type A)	0.00103	0.00209	0.00188	0.00084	0.00177	0.00263	0.00234	0.00095	0.00261	0.00285	0.00225
Expanded Uncertainty (K=2)	0.00221	0.00426	0.00384	0.00187	0.00362	0.00532	0.00474	0.00206	0.00528	0.00575	0.00457

Dimension X for the large paper part is .374 ± .004 inches. The reported uncertainty is based on a standards uncertainty multiplied by a coverage factor k=2, proving a level of confidence of 95%.

Table D.10

Measurement Uncertainty plotting data for Large Paper Part X Dimension

Descriptoin	1	2	3	4	5	6	7	8	9	10
+ 3 Sigma	0.38146	0.38146	0.38146	0.38146	0.38146	0.38146	0.38146	0.38146	0.38146	0.38146
- 3 Sigma	0.36797	0.36797	0.36797	0.36797	0.36797	0.36797	0.36797	0.36797	0.36797	0.36797
.374+.004	0.37800	0.37800	0.37800	0.37800	0.37800	0.37800	0.37800	0.37800	0.37800	0.37800
.374-.004	0.37000	0.37000	0.37000	0.37000	0.37000	0.37000	0.37000	0.37000	0.37000	0.37000
A	0.37510	0.37838	0.37529	0.37255	0.37391	0.37437	0.37431	0.37237	0.37366	0.37140
B	0.37255	0.37510	0.37431	0.37237	0.37529	0.37140	0.37437	0.37391	0.37838	0.37366
C	0.37233	0.37570	0.37142	0.37363	0.37342	0.37407	0.37464	0.37431	0.37087	0.37697
D	0.37326	0.37688	0.37165	0.37469	0.37727	0.37827	0.37205	0.37420	0.37572	0.37974
E	0.37361	0.37967	0.37538	0.37357	0.37331	0.37815	0.37696	0.37212	0.37632	0.37568
F	0.37414	0.38018	0.37536	0.37359	0.37233	0.37517	0.37873	0.37361	0.37631	0.37507

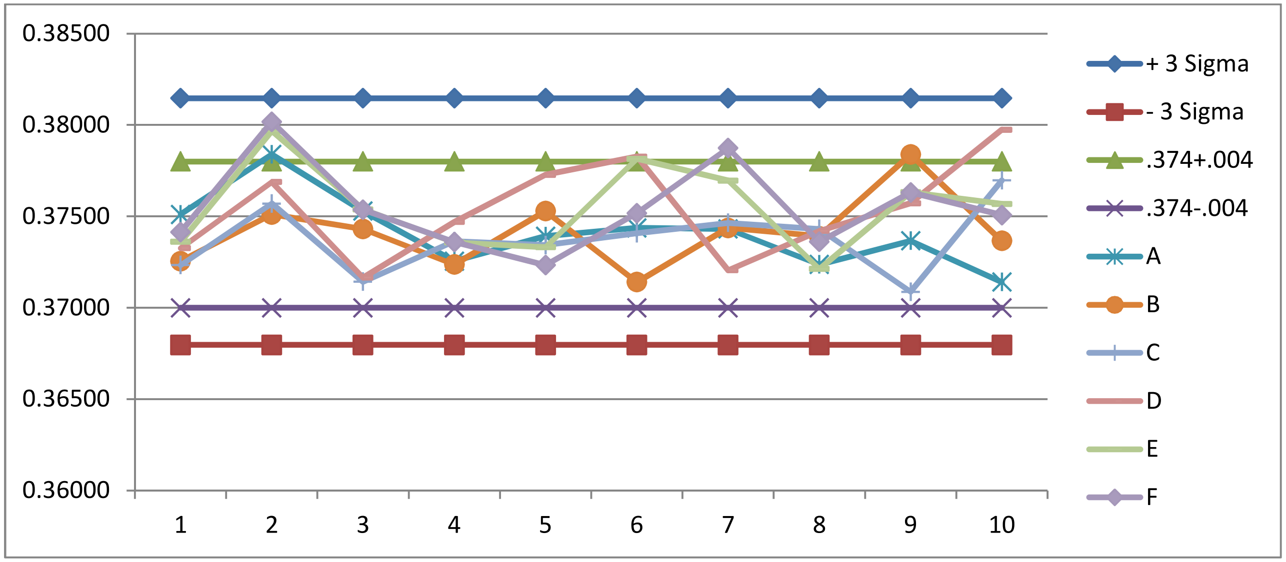


Figure D. 3 Graphic Result for Measurement Uncertainty for Large Paper Part X dimension

Table D. 11

Measurement Uncertainty Results for the Large Paper Part Y Dimension

Specification of Equipment	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	Summary
Uncertainty of Calibrator (Type B)	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040
Trial	**Part 1**	**Part 2**	**Part 3**	**Part 4**	**Part 5**	**Part 6**	**Part 7**	**Part 8**	**Part 9**	**Part 10**	
A	0.37593	0.37791	0.37340	0.37409	0.37474	0.37401	0.37441	0.37787	0.37131	0.37159	
B	0.37587	0.37798	0.37707	0.37570	0.37561	0.37391	0.37410	0.37917	0.37730	0.37878	
C	0.37867	0.37479	0.37270	0.37564	0.37211	0.37338	0.37642	0.37126	0.37634	0.37572	
D	0.37552	0.37756	0.37708	0.37637	0.37537	0.37614	0.37813	0.37453	0.37310	0.37648	
E	0.37384	0.37823	0.37408	0.37512	0.37858	0.37833	0.37709	0.37653	0.37471	0.37619	
F	0.37483	0.37874	0.37455	0.37582	0.37815	0.37685	0.37796	0.37907	0.37517	0.37461	Statistics
Sum	2.25466	2.26521	2.24888	2.25274	2.25456	2.25262	2.25811	2.25843	2.24793	2.25337	13.52867
Mean	0.37578	0.37754	0.37481	0.37546	0.37576	0.37544	0.37635	0.37641	0.37466	0.37556	0.37580
Maximum Value	0.37867	0.37874	0.37708	0.37637	0.37858	0.37833	0.37813	0.37917	0.37730	0.37878	0.37874
Minimum Value	0.37384	0.37479	0.37270	0.37409	0.37211	0.37338	0.37410	0.37126	0.37131	0.37159	0.37211
Range	0.00483	0.00395	0.00438	0.00228	0.00647	0.00495	0.00403	0.00791	0.00599	0.00719	0.00663
Standard Deviation	0.00162	0.00140	0.00186	0.00078	0.00237	0.00197	0.00174	0.00306	0.00218	0.00238	0.00182
+ 3 Sigma	0.38064	0.38174	0.38039	0.37780	0.38288	0.38136	0.38157	0.38559	0.38119	0.38270	0.38127
- 3 Sigma	0.37092	0.37333	0.36923	0.37312	0.36864	0.36952	0.37113	0.36722	0.36812	0.36842	0.37033
Median	0.37570	0.37795	0.37432	0.37567	0.37549	0.37508	0.37676	0.37720	0.37494	0.37596	0.37567
Uncertainty (Type A)	0.00162	0.00140	0.00186	0.00078	0.00237	0.00197	0.00174	0.00306	0.00218	0.00238	0.00182
Expanded Uncertainty (K=2)	0.00334	0.00292	0.00381	0.00176	0.00482	0.00403	0.00357	0.00618	0.00443	0.00483	0.00373

Dimension Y for the large paper part is .376 ± .004 inches. The reported uncertainty is based on a standards uncertainty multiplied by a coverage factor k=2, proving a level of confidence of 95%.

Table D. 12

Measurement Uncertainty plotting data for Paper Part Y Dimension

Description	Part 1	Part 2	Part 3	Part 4	Part 5	Part 6	Part 7	Part 8	Part 9	Part 10
+ 3 Sigma	0.38127	0.38127	0.38127	0.38127	0.38127	0.38127	0.38127	0.38127	0.38127	0.38127
- 3 Sigma	0.37033	0.37033	0.37033	0.37033	0.37033	0.37033	0.37033	0.37033	0.37033	0.37033
.376+.004	0.38000	0.38000	0.38000	0.38000	0.38000	0.38000	0.38000	0.38000	0.38000	0.38000
.376-.004	0.37200	0.37200	0.37200	0.37200	0.37200	0.37200	0.37200	0.37200	0.37200	0.37200
A	0.37593	0.37791	0.37340	0.37409	0.37474	0.37401	0.37441	0.37787	0.37131	0.37159
B	0.37587	0.37798	0.37707	0.37570	0.37561	0.37391	0.37410	0.37917	0.37730	0.37878
C	0.37867	0.37479	0.37270	0.37564	0.37211	0.37338	0.37642	0.37126	0.37634	0.37572
D	0.37552	0.37756	0.37708	0.37637	0.37537	0.37614	0.37813	0.37453	0.37310	0.37648
E	0.37384	0.37823	0.37408	0.37512	0.37858	0.37833	0.37709	0.37653	0.37471	0.37619
F	0.37483	0.37874	0.37455	0.37582	0.37815	0.37685	0.37796	0.37907	0.37517	0.37461

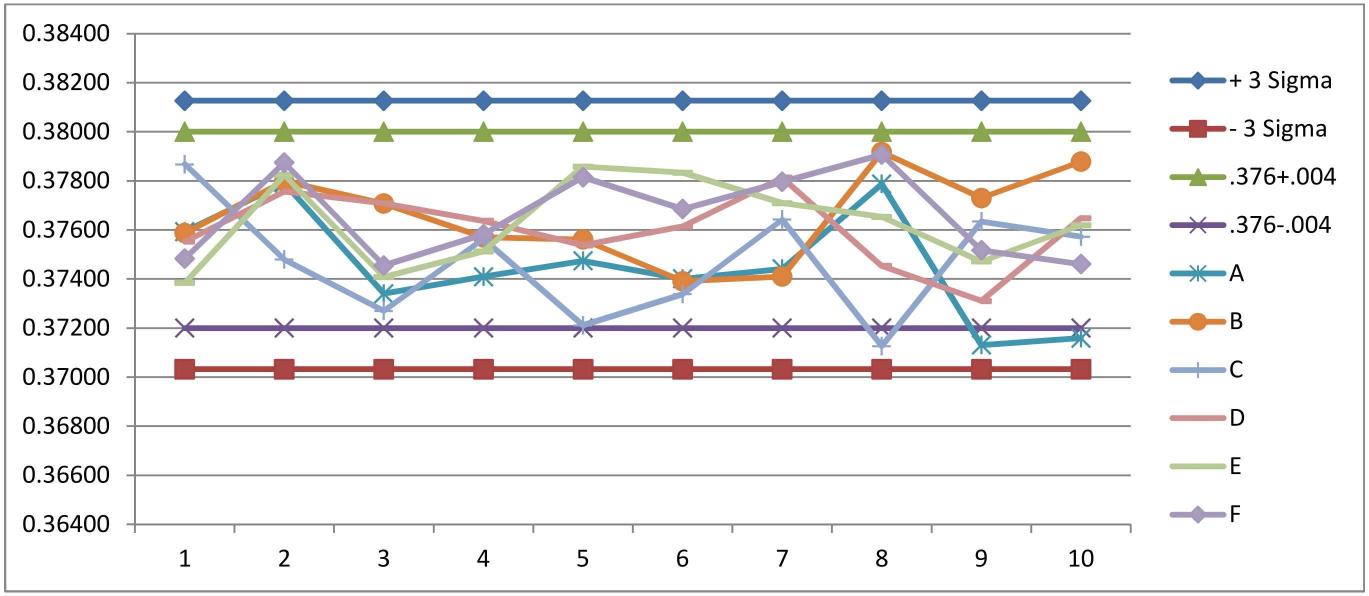


Figure D. 4 Graphic Result for Measurement Uncertainty for Large Paper Part Y dimension

Table D. 13

Measurement Uncertainty Results for the Large Paper Part A Dimension

	Part 1	Part 2	Part 3	Part 4	Part 5	Part 6	Part 7	Part 8	Part 9	Part 10	Summary
Specification of Equipment	+/-3	+/-3	+/-3	+/-3	+/-3	+/-3	+/-3	+/-3	+/-3	+/-3	+/-3
Uncertainty of Calibrator (Type B)	0.17321	0.17321	0.17321	0.17321	0.17321	0.17321	0.17321	0.17321	0.17321	0.17321	0.17321
A	76.60979	76.10609	75.90718	77.12264	75.00563	77.54783	74.44439	76.53851	75.83974	76.57765	
B	74.19213	75.71709	75.21196	76.90372	75.99273	76.23964	76.14118	74.71845	77.23808	76.17390	
C	74.37050	75.09241	76.16518	76.78271	75.78139	76.37699	77.08609	76.21474	76.68921	76.06345	
D	76.43072	77.34260	77.02476	76.06202	76.21550	75.42715	74.51484	76.89203	76.10068	76.08704	
E	76.80064	76.41139	75.86975	76.36032	74.10515	76.73780	74.40227	76.56201	76.05384	77.30157	
F	77.01106	76.02542	76.06743	76.98131	74.49339	75.68337	75.11266	76.84272	75.64300	77.07797	Statistics
Sum	455.41484	456.69500	456.24626	460.21272	451.59379	458.01278	451.70143	457.76846	457.56455	459.28158	2734.46198
Mean	75.90247	76.11583	76.04104	76.70212	75.26563	76.33546	75.28357	76.29474	76.26076	76.54693	75.95728
Maximum Value	77.01106	77.34260	77.02476	77.12264	76.21550	77.54783	77.08609	76.89203	77.23808	77.30157	77.54783
Minimum Value	74.19213	75.09241	75.21196	76.06202	74.10515	75.42715	74.40227	74.71845	75.64300	76.06345	74.10515
Range	2.81893	2.25019	1.81280	1.06062	2.11035	2.12068	2.68382	2.17358	1.59508	1.23812	3.44268
Standard Deviation	1.27179	0.74926	0.58625	0.40706	0.86112	0.76064	1.10324	0.80981	0.59431	0.53607	0.89464
+ 3 Sigma	79.71784	78.36362	77.79979	77.92329	77.84898	78.61739	78.59328	78.72418	78.04370	78.15513	78.64120
- 3 Sigma	72.08711	73.86805	74.28229	75.48095	72.68228	74.05354	71.97387	73.86530	74.47781	74.93873	73.27336
Median	76.52026	76.06576	75.98731	76.84322	75.39351	76.30832	74.81375	76.55026	76.07726	76.37578	76.06473
Uncertainty (Type A)	1.27179	0.74926	0.58625	0.40706	0.86112	0.76064	1.10324	0.80981	0.59431	0.53607	0.89464
Expanded Uncertainty (K=2)	2.56706	1.53804	1.22260	0.88475	1.75673	1.56022	2.23350	1.65626	1.23808	1.12671	1.82251

Dimension A for the large paper part is .76 ± 2 degrees. The reported uncertainty is based on a standards uncertainty multiplied by a coverage factor k=2, proving a level of confidence of 95%.

Table D. 14

Measurement Uncertainty plotting data for Large Paper Part A Dimension

Description	1	2	3	4	5	6	7	8	9	10
+ 3 Sigma	78.64120	78.64120	78.64120	78.64120	78.64120	78.64120	78.64120	78.64120	78.64120	78.64120
- 3 Sigma	73.27336	73.27336	73.27336	73.27336	73.27336	73.27336	73.27336	73.27336	73.27336	73.27336
76+2	78.00000	78.00000	78.00000	78.00000	78.00000	78.00000	78.00000	78.00000	78.00000	78.00000
76-2	74.00000	74.00000	74.00000	74.00000	74.00000	74.00000	74.00000	74.00000	74.00000	74.00000
A	76.60979	76.10609	75.90718	77.12264	75.00563	77.54783	74.44439	76.53851	75.83974	76.57765
B	74.19213	75.71709	75.21196	76.90372	75.99273	76.23964	76.14118	74.71845	77.23808	76.17390
C	74.37050	75.09241	76.16518	76.78271	75.78139	76.37699	77.08609	76.21474	76.68921	76.06345
D	76.43072	77.34260	77.02476	76.06202	76.21550	75.42715	74.51484	76.89203	76.10068	76.08704
E	76.80064	76.41139	75.86975	76.36032	74.10515	76.73780	74.40227	76.56201	76.05384	77.30157
F	77.01106	76.02542	76.06743	76.98131	74.49339	75.68337	75.11266	76.84272	75.64300	77.07797

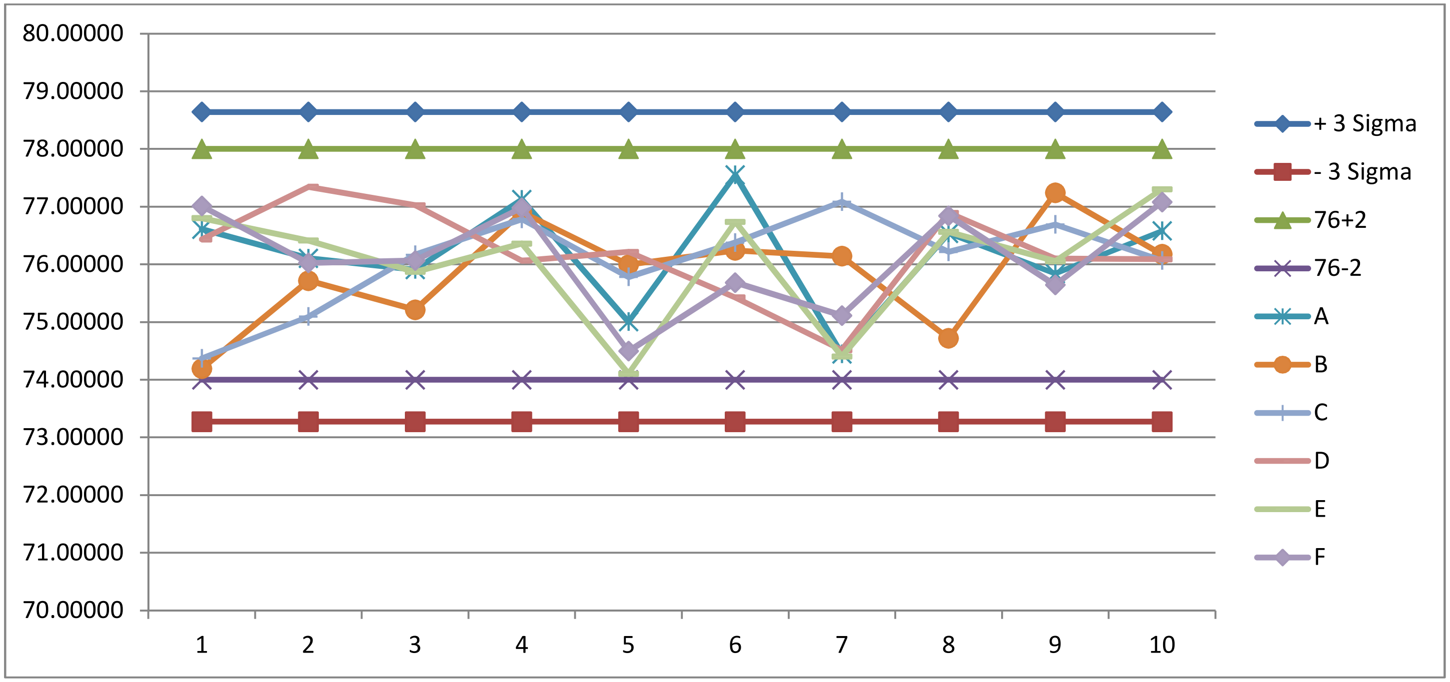


Figure D. 5 Graphic Result for Measurement Uncertainty for Large Paper Part A dimension

AIAG Gage R&R Results for the Large Paper Part X Dimension

Gage R&R for X

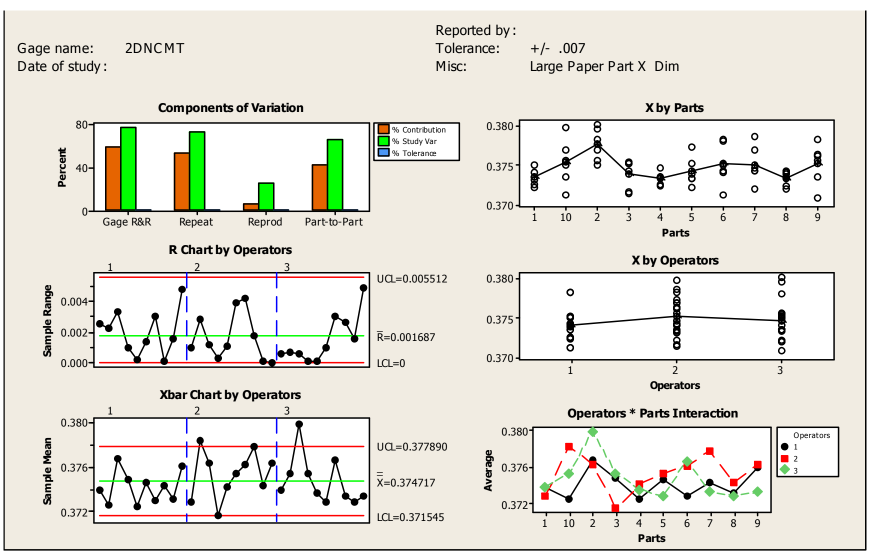
Gage name: 2DNCMT
Date of study:
Reported by:
Tolerance: +/- .007
Misc: Large Paper Part X Dim

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000025	58.32
Repeatability	0.0000022	52.15
Reproducibility	0.0000003	6.18
Part-To-Part	0.0000018	41.68
Total Variation	0.0000043	100.00

Process tolerance = 10

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.0015817	0.0094901	76.37	0.09
Repeatability	0.0014956	0.0089734	72.21	0.09
Reproducibility	0.0005148	0.0030887	24.86	0.03
Part-To-Part	0.0013370	0.0080220	64.56	0.08
Total Variation	0.0020711	0.0124264	100.00	0.12

Number of Distinct Categories = 1



AIAG Gage R&R Results for the Large Paper Part Y Dimension

Gage R&R for Y

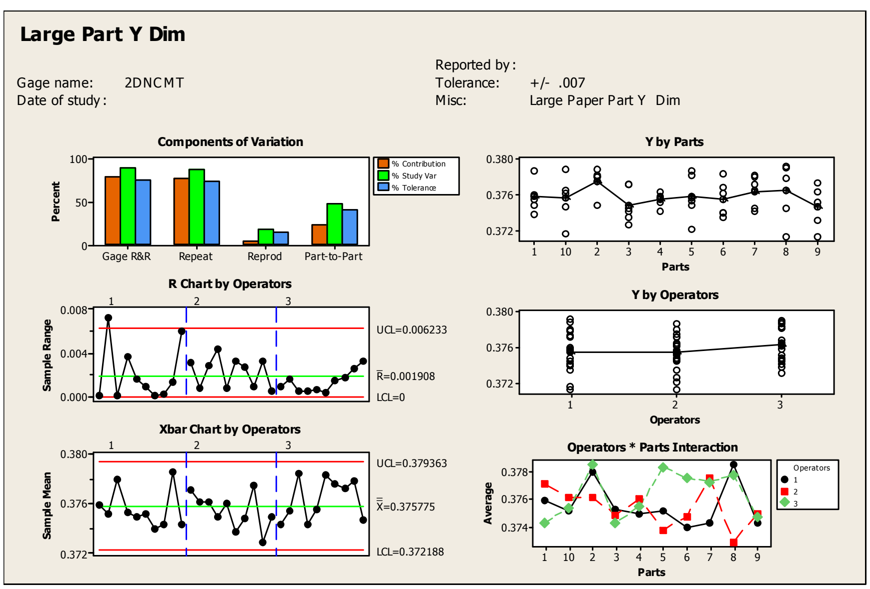
Gage name: 2DNCMT
Date of study:
Reported by:
Tolerance: +/- .007
Misc: Large Paper Part Y Dim

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000030	78.37
Repeatability	0.0000029	75.43
Reproducibility	0.0000001	2.93
Part-To-Part	0.0000008	21.63
Total Variation	0.0000038	100.00

Process tolerance = 0.014

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.0017238	0.0103425	88.53	73.88
Repeatability	0.0016912	0.0101472	86.85	72.48
Reproducibility	0.0003335	0.0020008	17.13	14.29
Part-To-Part	0.0009057	0.0054340	46.51	38.81
Total Variation	0.0019472	0.0116832	100.00	83.45

Number of Distinct Categories = 1



AIAG Gage R&R Results the Large Paper Part A Dimension

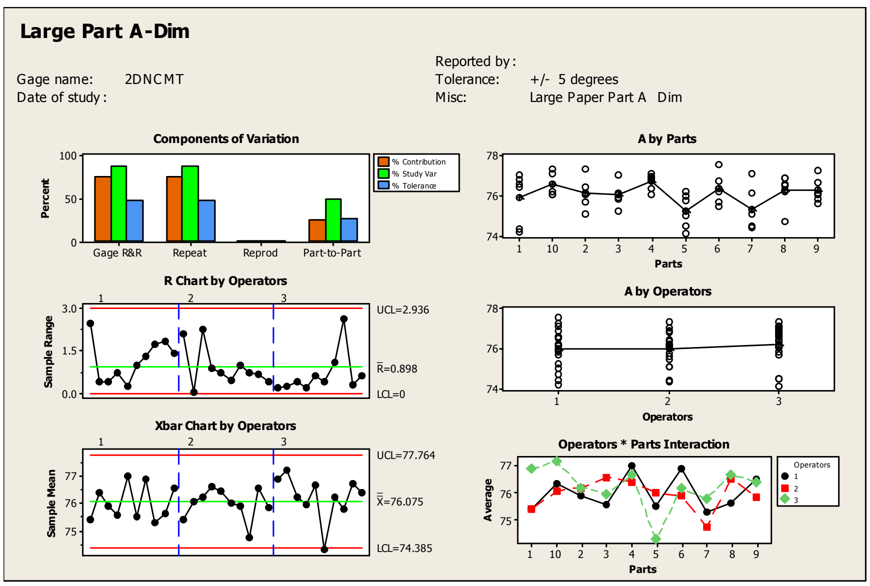
```
Gage name:        2DNCMT
Date of study:
Reported by:
Tolerance:        +/-  5 degrees
Misc:             Large Paper Part A  Dim
```

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.634414	75.66
Repeatability	0.634414	75.66
Reproducibility	0.000000	0.00
Part-To-Part	0.204056	24.34
Total Variation	0.838470	100.00

Process tolerance = 10

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.796501	4.77901	86.98	47.79
Repeatability	0.796501	4.77901	86.98	47.79
Reproducibility	0.000000	0.00000	0.00	0.00
Part-To-Part	0.451726	2.71036	49.33	27.10
Total Variation	0.915680	5.49408	100.00	54.94

Number of Distinct Categories = 1



Honest Gage R&R Results for the Large Paper Part

Table D.15

Honest Gage R&R CRR and ICC Results for Large Paper Part

Honest Gage R&R Results	X Dimension Value	Y Dimension Value	A Dimension Value
CRR	58.00	78.94	75.66
ICC	42.00	21.05	24.33
Monitor Class	3 – Acceptable	3 - Acceptable	3 - Acceptable

CAD Overlay Result for the Large Paper Part. Figure D.3 shows the fit of the large paper part with a ±.006 inch tolerance.

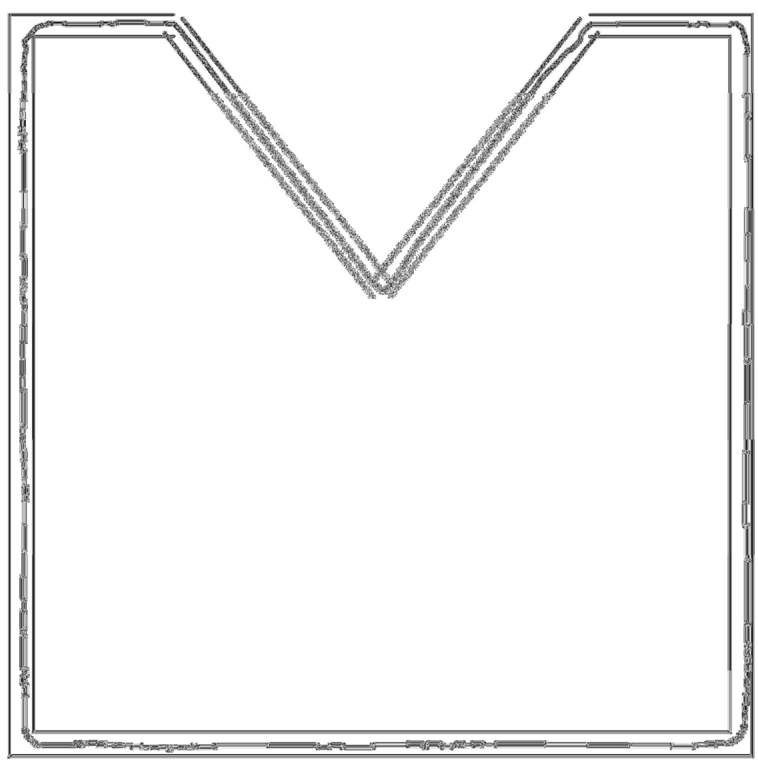


Figure D.3 CAD Overlay on the Large Paper Part

GAGE R&R STUDY DATA AND MINITAB RESULTS FOR THE SMALL PAPER PART

This section contains the following information related to the small paper part.

- Dimensioned Drawing
- Gage R&R Data
- AIAG Gage R&R results (Minitab Format) for each dimension measured.
- Honest Gage R&R results (Excel Format) for each dimension measured.
- CAD Overlay Examples showing the accuracy of the 2DNCMT.

Dimensioned Drawing of Small Paper Part. A dimensioned drawing of the small paper part is shown in Figure D.4.

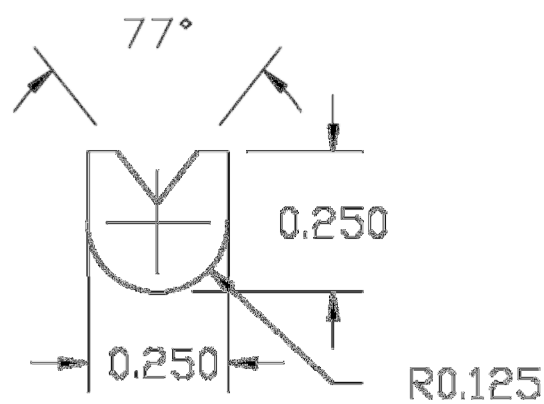


Figure D.4 Dimensioned Drawing of the Small Paper Part

GAGE R&R Data for the Small Paper Part

Table D.16

2DNCMT Gage R&R Data for Small Paper Part

StdOrder	RunOrder	Parts	Operators	X	Y	D	A
1	1	1	1	0.25139	0.24766	0.25192	76.05160
2	2	1	2	0.25006	0.24726	0.25067	76.18147
3	3	1	3	0.24710	0.24566	0.24542	75.90816
4	4	2	1	0.25036	0.25122	0.24521	76.80306
5	5	2	2	0.24994	0.25130	0.24487	76.04115
6	6	2	3	0.25031	0.24661	0.25085	76.05160
7	7	3	1	0.24992	0.24658	0.24379	76.43059
8	8	3	2	0.24944	0.24671	0.24272	75.79878
9	9	3	3	0.24800	0.24818	0.25041	75.07882
10	10	4	1	0.24787	0.24643	0.24619	75.90816
11	11	4	2	0.24797	0.24573	0.24553	76.15035
12	12	4	3	0.24974	0.24781	0.24599	75.78615
13	13	5	1	0.25217	0.24918	0.24707	75.30450
14	14	5	2	0.25222	0.24926	0.24625	74.92086
15	15	5	3	0.25129	0.24872	0.24621	75.30450
16	16	6	1	0.24917	0.24935	0.25150	75.07882
17	17	6	2	0.24980	0.25067	0.24858	74.66076
18	18	6	3	0.24975	0.25061	0.24461	76.80306
19	19	7	1	0.24807	0.25101	0.25141	76.60097
20	20	7	2	0.24966	0.24997	0.24936	75.98485
21	21	7	3	0.24772	0.25066	0.25106	76.60097
22	22	8	1	0.25075	0.24882	0.24698	75.78615
23	23	8	2	0.24989	0.24831	0.24649	75.95347
24	24	8	3	0.24795	0.24773	0.25073	74.10422
25	25	9	1	0.24851	0.24830	0.25130	74.10422
26	26	9	2	0.24888	0.24891	0.24841	74.65450
27	27	9	3	0.25212	0.24814	0.25297	74.72672
28	28	10	1	0.25260	0.24859	0.25342	74.72672
29	29	10	2	0.25257	0.24833	0.25316	74.65411
30	30	10	3	0.24936	0.24603	0.24324	76.43059
31	31	1	1	0.25119	0.24736	0.25140	75.81772
32	32	1	2	0.25013	0.24721	0.25159	75.88669
33	33	1	3	0.24942	0.24681	0.24224	76.50508
34	34	2	1	0.25048	0.25121	0.24490	75.61662
35	35	2	2	0.25064	0.25136	0.24506	76.00877
36	36	2	3	0.24685	0.24626	0.24466	75.66132

StdOrder	RunOrder	Parts	Operators	X	Y	D	A
37	37	3	1	0.24994	0.24732	0.24294	76.50508
38	38	3	2	0.24898	0.24817	0.24301	76.37054
39	39	3	3	0.25224	0.24759	0.25253	74.43373
40	40	4	1	0.24709	0.24650	0.24489	75.66132
41	41	4	2	0.24786	0.24614	0.24596	75.66824
42	42	4	3	0.24943	0.24961	0.24783	75.04440
43	43	5	1	0.25244	0.24922	0.24775	74.94110
44	44	5	2	0.25248	0.24854	0.24690	75.02699
45	45	5	3	0.25016	0.25089	0.25559	75.61662
46	46	6	1	0.24934	0.24952	0.24776	75.04440
47	47	6	2	0.25067	0.24978	0.24942	75.78617
48	48	6	3	0.24961	0.24950	0.24606	75.53683
49	49	7	1	0.24965	0.25238	0.24955	75.41122
50	50	7	2	0.24981	0.25027	0.24979	76.18650
51	51	7	3	0.24781	0.24748	0.24865	74.60510
52	52	8	1	0.24979	0.24969	0.24624	75.53683
53	53	8	2	0.25020	0.24935	0.24713	75.32006
54	54	8	3	0.25232	0.24911	0.24764	74.94110
55	55	9	1	0.24839	0.24806	0.24903	74.60510
56	56	9	2	0.24941	0.24731	0.24877	73.88501
57	57	9	3	0.25047	0.24665	0.25069	75.81772
58	58	10	1	0.25270	0.24803	0.25299	74.43373
59	59	10	2	0.25271	0.24901	0.25333	74.70269
60	60	10	3	0.24907	0.25224	0.24857	75.41122

Process Capability Results for the Small Paper Part 17

Table D. 17

Process Capability Results for Small Paper Part X Dimension

Part	A	B	C	D	E	F	P Xbar	P Range
1	0.25139	0.25119	0.25006	0.25013	0.24893	0.25054	0.250	0.002
2	0.25036	0.25048	0.24994	0.25064	0.25031	0.25038	0.250	0.001
3	0.24992	0.24994	0.24944	0.24898	0.24879	0.24899	0.249	0.001
4	0.24787	0.24709	0.24797	0.24786	0.24974	0.24943	0.248	0.003
5	0.25217	0.25244	0.25222	0.25248	0.25129	0.25016	0.252	0.002
6	0.24917	0.24934	0.24980	0.25067	0.24975	0.24961	0.250	0.002
7	0.24807	0.24965	0.24966	0.24981	0.24772	0.24781	0.249	0.002
8	0.25075	0.24979	0.24989	0.25020	0.25027	0.24995	0.250	0.001
9	0.24851	0.24839	0.24888	0.24941	0.25212	0.25047	0.250	0.004
10	0.25260	0.25270	0.25257	0.25271	0.24936	0.24907	0.252	0.004
						Sum	2.500	0.021

nominal	tolerance
0.25	0.007

Xbar =	0.2500
Rbar =	0.0021
Sigma =	0.0008
6-Sigma =	0.0050
USL =	0.257
LSL =	0.243
Cp =	2.789
CpU =	2.790
CpL =	2.788
Cpk =	2.788

Table D. 18

Process Capability Results for Small Paper Part Y Dimension

Part	A	B	C	D	E	F	P Xbar	P Range
1	0.24766	0.24736	0.24726	0.24721	0.24768	0.24727	0.247	0.000
2	0.25122	0.25121	0.25130	0.25136	0.25135	0.25169	0.251	0.000
3	0.24658	0.24732	0.24671	0.24817	0.24705	0.24810	0.247	0.002
4	0.24643	0.24650	0.24573	0.24614	0.24781	0.24961	0.247	0.004
5	0.24918	0.24922	0.24926	0.24854	0.24872	0.25089	0.249	0.002
6	0.24935	0.24952	0.25067	0.24978	0.25061	0.24950	0.250	0.001
7	0.25101	0.25238	0.24997	0.25027	0.25066	0.24748	0.250	0.005
8	0.24882	0.24969	0.24831	0.24935	0.24813	0.24784	0.249	0.002
9	0.24830	0.24806	0.24891	0.24731	0.24814	0.24665	0.248	0.002
10	0.24859	0.24803	0.24833	0.24901	0.24603	0.25224	0.249	0.006
						Sum	2.488	0.025

nominal	tolerance
0.25	0.007

Xbar =	0.2488
Rbar =	0.0025
Sigma =	0.0008
6-Sigma =	0.0050
USL =	0.257
LSL =	0.243
Cp =	2.789
CpU =	3.271
CpL =	2.307
Cpk =	2.307

Table D. 19

Process Capability Results for Small Paper Part D Dimension

Part	A	B	C	D	E	F		P Xbar	P Range
1	0.25192	0.25140	0.25067	0.25159	0.25168	0.25165		0.251	0.001
2	0.24521	0.24490	0.24487	0.24506	0.24409	0.24418		0.245	0.001
3	0.24379	0.24294	0.24272	0.24301	0.24425	0.24360		0.243	0.002
4	0.24619	0.24489	0.24553	0.24596	0.24599	0.24783		0.246	0.003
5	0.24707	0.24775	0.24625	0.24690	0.24621	0.25559		0.248	0.009
6	0.25150	0.24776	0.24858	0.24942	0.24461	0.24606		0.248	0.007
7	0.25141	0.24955	0.24936	0.24979	0.25106	0.24865		0.250	0.003
8	0.24698	0.24624	0.24649	0.24713	0.24681	0.24609		0.247	0.001
9	0.25130	0.24903	0.24841	0.24877	0.25297	0.25069		0.250	0.005
10	0.25342	0.25299	0.25316	0.25333	0.24324	0.24857		0.251	0.010
						Sum		2.480	0.042

nominal	tolerance
0.25	0.007

Xbar =	0.2480
Rbar =	0.0042
Sigma =	0.0008
6-Sigma =	0.0050
USL =	0.257
LSL =	0.243
Cp =	2.789
CpU =	3.605
CpL =	1.973
Cpk =	1.973

Measurement Uncertainty Results for the Small Paper Part

Table D. 20

Measurement Uncertainty Results for the Small Paper Part X Dimension

Specification of Equipment	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	Summary
Uncertainty of Calibrator (Type B)	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040
Trial	**Part 1**	**Part 2**	**Part 3**	**Part 4**	**Part 5**	**Part 6**	**Part 7**	**Part 8**	**Part 9**	**Part 10**	
A	0.25139	0.25036	0.24992	0.24787	0.25217	0.24917	0.24807	0.25075	0.24851	0.2526	
B	0.25119	0.25048	0.24994	0.24709	0.25244	0.24934	0.24965	0.24979	0.24839	0.2527	
C	0.25006	0.24994	0.24944	0.24797	0.25222	0.2498	0.24966	0.24989	0.24888	0.25257	
D	0.25013	0.25064	0.24786	0.25248	0.25067	0.24981	0.2502	0.25013	0.24941	0.25271	
E	0.24893	0.25031	0.24879	0.24974	0.25129	0.24975	0.24772	0.25027	0.25212	0.24936	
F	0.25054	0.25038	0.24899	0.24943	0.25016	0.24961	0.24781	0.24995	0.25047	0.24907	Statisitcs
Sum	1.50224	1.50211	1.49494	1.49458	1.50895	1.49748	1.49311	1.50078	1.49778	1.50901	15.00098
Mean	0.25037	0.25035	0.24916	0.24910	0.25149	0.24958	0.24885	0.25013	0.24963	0.25150	0.25002
Maximum Value	0.25139	0.25064	0.24994	0.25248	0.25244	0.24981	0.25020	0.25075	0.25212	0.25271	0.25271
Minimum Value	0.24893	0.24994	0.24786	0.24709	0.25016	0.24917	0.24772	0.24979	0.24839	0.24907	0.24709
Range	0.00246	0.00070	0.00208	0.00539	0.00228	0.00064	0.00248	0.00096	0.00373	0.00364	0.00562
Standard Deviation	0.00089	0.00023	0.00079	0.00194	0.00094	0.00027	0.00110	0.00035	0.00144	0.00177	0.00137
+ 3 Sigma	0.25305	0.25105	0.25153	0.25491	0.25430	0.25038	0.25216	0.25118	0.25394	0.25683	0.25413
- 3 Sigma	0.24770	0.24965	0.24679	0.24328	0.24868	0.24878	0.24554	0.24908	0.24532	0.24618	0.24590
Median	0.25034	0.25037	0.24922	0.24870	0.25173	0.24968	0.24886	0.25004	0.24915	0.25259	0.24994
Uncertainty (Type A)	0.00089	0.00023	0.00079	0.00194	0.00094	0.00027	0.00110	0.00035	0.00144	0.00177	0.00137
Expanded Uncertainty (K=2)	0.00196	0.00093	0.00177	0.00396	0.00204	0.00097	0.00235	0.00107	0.00298	0.00364	0.00286

Dimension X for the small paper part is .250 ± .003 inches. The reported uncertainty is based on a standards uncertainty multiplied by a coverage factor k=2, proving a level of confidence of 95%.

Table D. 21

Measurement Uncertainty plotting data for Small Paper Part X Dimension

Description	1	2	3	4	5	6	7	8	9	10
+ 3 Sigma	0.25413	0.25413	0.25413	0.25413	0.25413	0.25413	0.25413	0.25413	0.25413	0.25413
- 3 Sigma	0.24590	0.24590	0.24590	0.24590	0.24590	0.24590	0.24590	0.24590	0.24590	0.24590
.250+.003	0.25300	0.25300	0.25300	0.25300	0.25300	0.25300	0.25300	0.25300	0.25300	0.25300
.250-.003	0.24700	0.24700	0.24700	0.24700	0.24700	0.24700	0.24700	0.24700	0.24700	0.24700
A	0.25139	0.25036	0.24992	0.24787	0.25217	0.24917	0.24807	0.25075	0.24851	0.2526
B	0.25119	0.25048	0.24994	0.24709	0.25244	0.24934	0.24965	0.24979	0.24839	0.2527
C	0.25006	0.24994	0.24944	0.24797	0.25222	0.2498	0.24966	0.24989	0.24888	0.25257
D	0.25013	0.25064	0.24786	0.25248	0.25067	0.24981	0.2502	0.25013	0.24941	0.25271
E	0.24893	0.25031	0.24879	0.24974	0.25129	0.24975	0.24772	0.25027	0.25212	0.24936
F	0.25054	0.25038	0.24899	0.24943	0.25016	0.24961	0.24781	0.24995	0.25047	0.24907

The measurement and uncertainty is 0.250+/.003 inches.

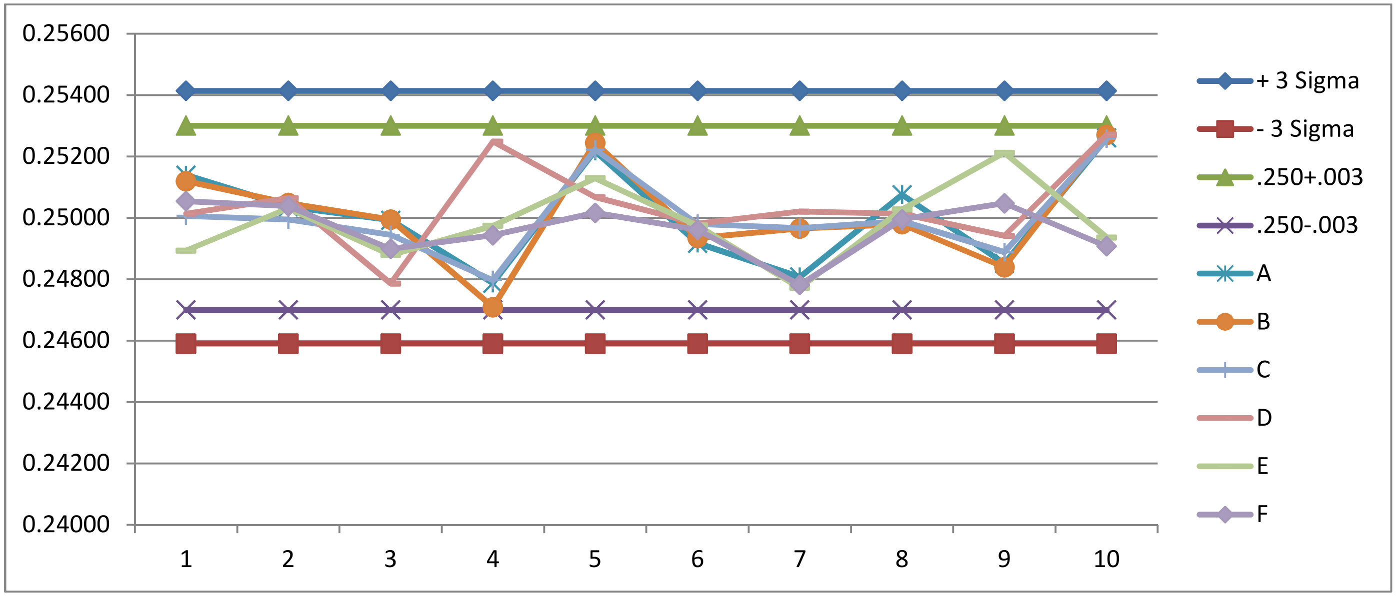


Figure D. 6 Graphic Result for Measurement Uncertainty for Small Paper Part X dimension

Table D. 22

Measurement Uncertainty Results for the Small Paper Part Y Dimension

Specification of Equipment	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007
Uncertainty of Calibrator (Type B)	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040
Trial	**Part 1**	**Part 2**	**Part 3**	**Part 4**	**Part 5**	**Part 6**	**Part 7**	**Part 8**	**Part 9**	**Part 10**	
A	0.25342	0.25192	0.25192	0.24521	0.24379	0.24619	0.24707	0.25150	0.25141	0.24698	
B	0.25299	0.25140	0.25140	0.24490	0.24294	0.24489	0.24775	0.24776	0.24955	0.24624	
C	0.25316	0.25067	0.25067	0.24487	0.24272	0.24553	0.24625	0.24858	0.24936	0.24649	
D	0.25333	0.25159	0.25159	0.24506	0.24301	0.24596	0.24690	0.24942	0.24979	0.24713	
E	0.24324	0.25168	0.25168	0.24409	0.24425	0.24599	0.24621	0.24461	0.25106	0.24681	Summary
F	0.24857	0.25165	0.25165	0.24418	0.24360	0.24783	0.25559	0.24606	0.24865	0.24609	Statistics
Sum	1.50471	1.50891	1.50891	1.46831	1.46031	1.47639	1.48977	1.48793	1.49982	1.47974	14.88480
Mean	0.25079	0.25149	0.25149	0.24472	0.24339	0.24607	0.24830	0.24799	0.24997	0.24662	0.24808
Maximum Value	0.25342	0.25192	0.25192	0.24521	0.24425	0.24783	0.25559	0.25150	0.25141	0.24713	0.25559
Minimum Value	0.24324	0.25067	0.25067	0.24409	0.24272	0.24489	0.24621	0.24461	0.24865	0.24609	0.24272
Range	0.01018	0.00125	0.00125	0.00112	0.00153	0.00294	0.00938	0.00689	0.00276	0.00104	0.01287
Standard Deviation	0.00414	0.00043	0.00043	0.00047	0.00059	0.00098	0.00362	0.00245	0.00106	0.00042	0.00329
+ 3 Sigma	0.26321	0.25278	0.25278	0.24612	0.24515	0.24901	0.25915	0.25533	0.25314	0.24787	0.25795
- 3 Sigma	0.23836	0.25019	0.25019	0.24331	0.24162	0.24312	0.23744	0.24065	0.24680	0.24537	0.23821
Median	0.25308	0.25162	0.25162	0.24489	0.24331	0.24598	0.24699	0.24817	0.24967	0.24665	0.24701
Uncertainty (Type A)	0.00414	0.00043	0.00043	0.00047	0.00059	0.00098	0.00362	0.00245	0.00106	0.00042	0.00329
Expanded Uncertainty (K=2)	0.00832	0.00118	0.00118	0.00124	0.00143	0.00212	0.00728	0.00496	0.00226	0.00116	0.00663

Dimension Y for the small paper part is .247 ± .007 inches. The reported uncertainty is based on a standards uncertainty multiplied by a coverage factor k=2, proving a level of confidence of 95%.

Table D. 23

Measurement Uncertainty plotting data for Small Paper Part Y Dimension

Description	1	2	3	4	5	6	7	8	9	10
+ 3 Sigma	0.25795	0.25795	0.25795	0.25795	0.25795	0.25795	0.25795	0.25795	0.25795	0.25795
- 3 Sigma	0.23821	0.23821	0.23821	0.23821	0.23821	0.23821	0.23821	0.23821	0.23821	0.23821
.247+.007	0.25400	0.25400	0.25400	0.25400	0.25400	0.25400	0.25400	0.25400	0.25400	0.25400
.247-.007	0.24000	0.24000	0.24000	0.24000	0.24000	0.24000	0.24000	0.24000	0.24000	0.24000
A	0.25342	0.25192	0.25192	0.24521	0.24379	0.24619	0.24707	0.25150	0.25141	0.24698
B	0.25299	0.25140	0.25140	0.24490	0.24294	0.24489	0.24775	0.24776	0.24955	0.24624
C	0.25316	0.25067	0.25067	0.24487	0.24272	0.24553	0.24625	0.24858	0.24936	0.24649
D	0.25333	0.25159	0.25159	0.24506	0.24301	0.24596	0.24690	0.24942	0.24979	0.24713
E	0.24324	0.25168	0.25168	0.24409	0.24425	0.24599	0.24621	0.24461	0.25106	0.24681
F	0.24857	0.25165	0.25165	0.24418	0.24360	0.24783	0.25559	0.24606	0.24865	0.24609

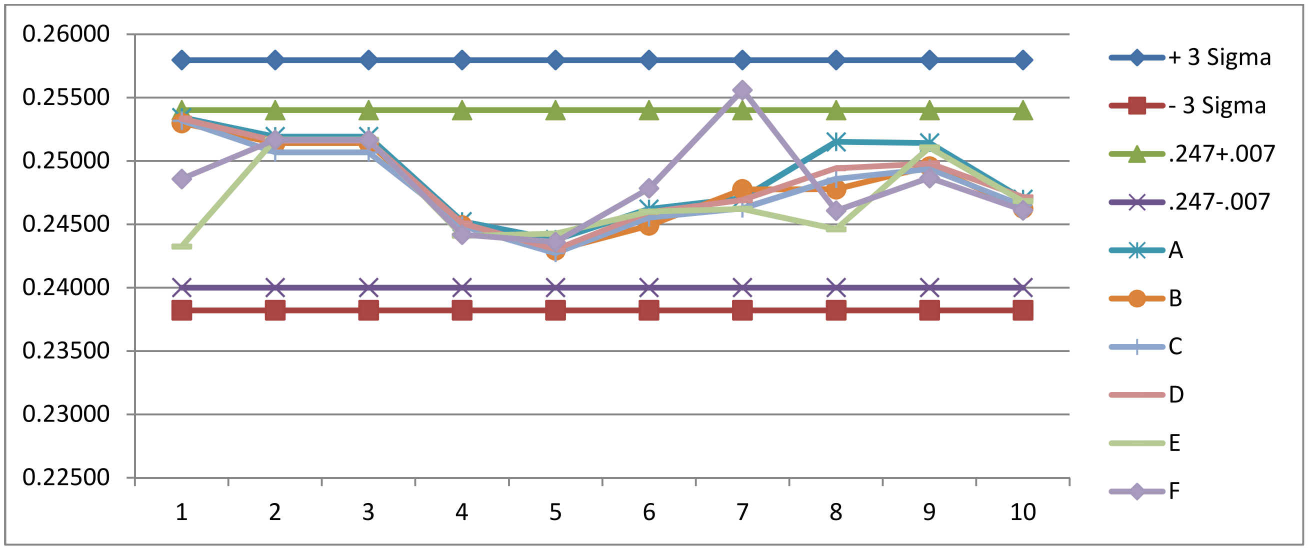


Figure D. 7 Graphic Result for Measurement Uncertainty for Small Paper Part Y Dimension

Table D. 24

Measurement Uncertainty Results for the Small Paper Part D Dimension

Specification of Equipment	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	+/-0.007	Summary
Uncertainty of Calibrator (Type B)	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040	0.00040
Trial	**Part 1**	**Part 2**	**Part 3**	**Part 4**	**Part 5**	**Part 6**	**Part 7**	**Part 8**	**Part 9**	**Part 10**	
A	0.24766	0.25122	0.24658	0.24643	0.24918	0.24935	0.25101	0.24882	0.2483	0.24859	
B	0.24736	0.25121	0.24732	0.2465	0.24922	0.24952	0.25238	0.24969	0.24806	0.24803	
C	0.24726	0.2513	0.24671	0.24573	0.24926	0.25067	0.24997	0.24831	0.24891	0.24833	
D	0.24721	0.25136	0.24614	0.24854	0.24978	0.25027	0.24935	0.24721	0.24731	0.24901	
E	0.24768	0.25135	0.24705	0.24781	0.24872	0.25061	0.25066	0.24813	0.24814	0.24603	
F	0.24727	0.25169	0.2481	0.24961	0.25089	0.2495	0.24748	0.24784	0.24665	0.25224	Statistics
Sum	1.48444	1.50813	1.48190	1.48462	1.49705	1.49992	1.50085	1.49000	1.48737	1.49223	8.97247
Mean	0.24741	0.25136	0.24698	0.24744	0.24951	0.24999	0.25014	0.24833	0.24790	0.24871	0.24924
Maximum Value	0.24768	0.25169	0.24810	0.24961	0.25089	0.25067	0.25238	0.24969	0.24891	0.25224	0.25238
Minimum Value	0.24721	0.25121	0.24614	0.24573	0.24872	0.24935	0.24748	0.24721	0.24665	0.24603	0.24573
Range	0.00047	0.00048	0.00196	0.00388	0.00217	0.00132	0.00490	0.00248	0.00226	0.00621	0.00665
Standard Deviation	0.00021	0.00018	0.00068	0.00148	0.00076	0.00060	0.00166	0.00085	0.00080	0.00202	0.00183
+ 3 Sigma	0.24804	0.25188	0.24902	0.25186	0.25178	0.25178	0.25512	0.25089	0.25029	0.25476	0.25473
- 3 Sigma	0.24678	0.25083	0.24494	0.24301	0.24724	0.24819	0.24516	0.24578	0.24550	0.24265	0.24374
Median	0.24732	0.25133	0.24688	0.24716	0.24924	0.24990	0.25032	0.24822	0.24810	0.24846	0.24943
Uncertainty (Type A)	0.00021	0.00018	0.00068	0.00148	0.00076	0.00060	0.00166	0.00085	0.00080	0.00202	0.00183
Expanded Uncertainty (K=2)	0.00091	0.00088	0.00158	0.00306	0.00171	0.00145	0.00342	0.00188	0.00179	0.00412	0.00375

Dimension D for the small paper part is .249 ± .004 inches. The reported uncertainty is based on a standards uncertainty multiplied by a coverage factor k=2, proving a level of confidence of 95%.

Table D. 25

Measurement Uncertainty plotting data for Small Paper Part D Dimension

Description	1	2	3	4	5	6	7	8	9	10
+ 3 Sigma	0.25473	0.25473	0.25473	0.25473	0.25473	0.25473	0.25473	0.25473	0.25473	0.25473
- 3 Sigma	0.24374	0.24374	0.24374	0.24374	0.24374	0.24374	0.24374	0.24374	0.24374	0.24374
.249+.004	0.25300	0.25300	0.25300	0.25300	0.25300	0.25300	0.25300	0.25300	0.25300	0.25300
.249-.004	0.24500	0.24500	0.24500	0.24500	0.24500	0.24500	0.24500	0.24500	0.24500	0.24500
A	0.24766	0.25122	0.24658	0.24643	0.24918	0.24935	0.25101	0.24882	0.2483	0.24859
B	0.24736	0.25121	0.24732	0.2465	0.24922	0.24952	0.25238	0.24969	0.24806	0.24803
C	0.24726	0.2513	0.24671	0.24573	0.24926	0.25067	0.24997	0.24831	0.24891	0.24833
D	0.24721	0.25136	0.24614	0.24854	0.24978	0.25027	0.24935	0.24721	0.24731	0.24901
E	0.24768	0.25135	0.24705	0.24781	0.24872	0.25061	0.25066	0.24813	0.24814	0.24603
F	0.24727	0.25169	0.2481	0.24961	0.25089	0.2495	0.24748	0.24784	0.24665	0.25224

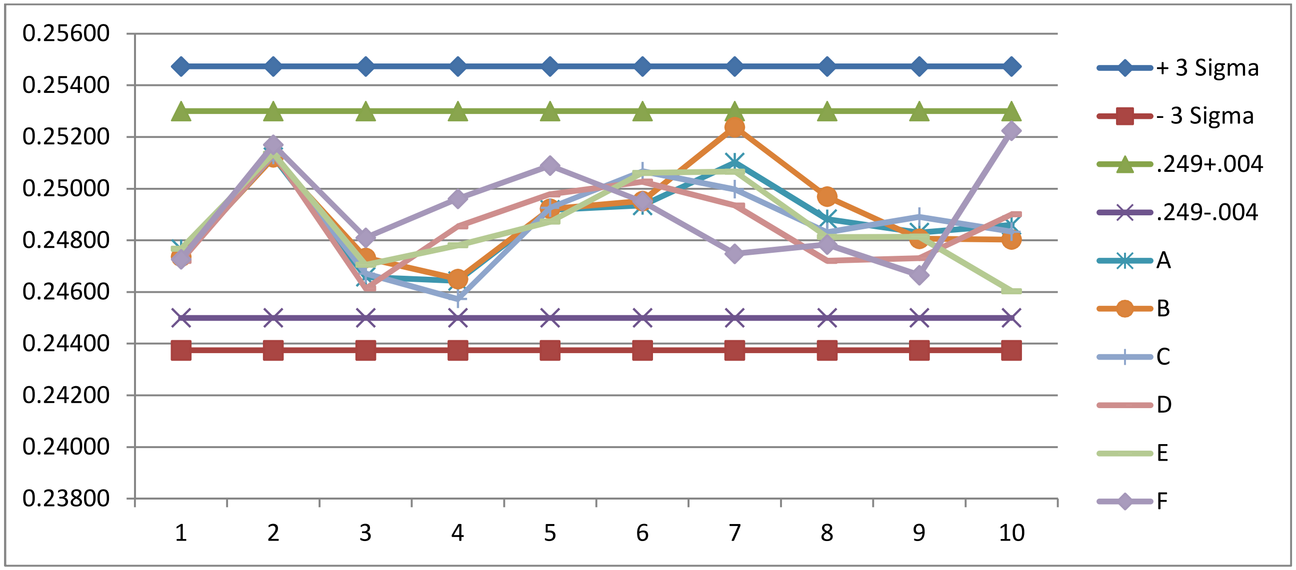
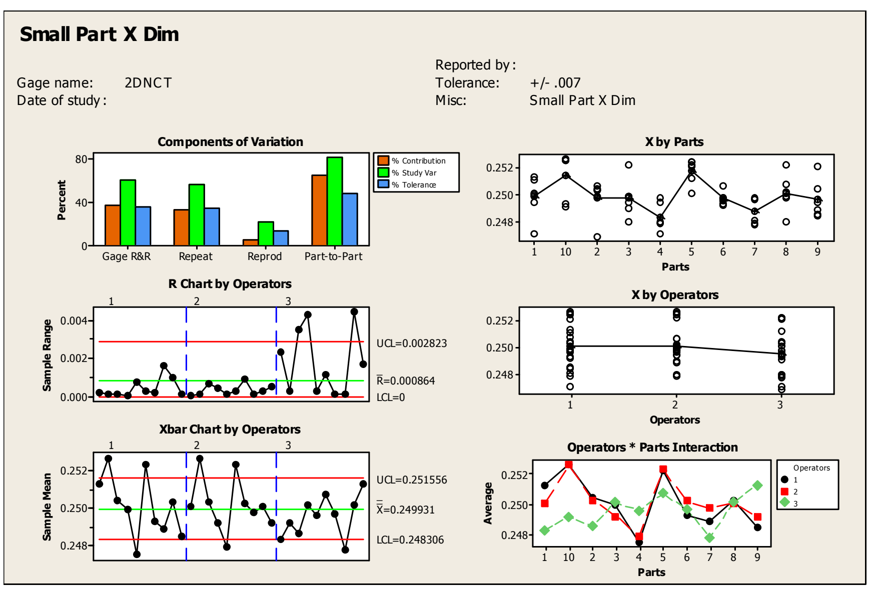


Figure D. 8 Graphic Result for Measurement Uncertainty for Small Paper Part D dimension

Gage R&R Results for the Small Paper Part X Dimension

```
Gage R&R for X

Gage name:        2DNCT
Date of study:
Reported by:
Tolerance:        +/- .007
Misc:             Small Part X Dim


                                     %Contribution
Source                   VarComp      (of VarComp)
Total Gage R&R         0.0000007            35.92
  Repeatability        0.0000006            31.63
  Reproducibility      0.0000001             4.28
Part-To-Part           0.0000012            64.08
Total Variation        0.0000019           100.00


Process tolerance = 0.014


                                    Study Var  %Study Var  %Tolerance
Source                 StdDev (SD)   (6 * SD)       (%SV)  (SV/Toler)
Total Gage R&R           0.0008162  0.0048971       59.93       34.98
  Repeatability          0.0007660  0.0045957       56.24       32.83
  Reproducibility        0.0002819  0.0016913       20.70       12.08
Part-To-Part             0.0010901  0.0065409       80.05       46.72
Total Variation          0.0013618  0.0081710      100.00       58.36


Number of Distinct Categories = 1
```



Gage R&R Results for the Small Paper Part Y Dimension

Gage R&R for Y

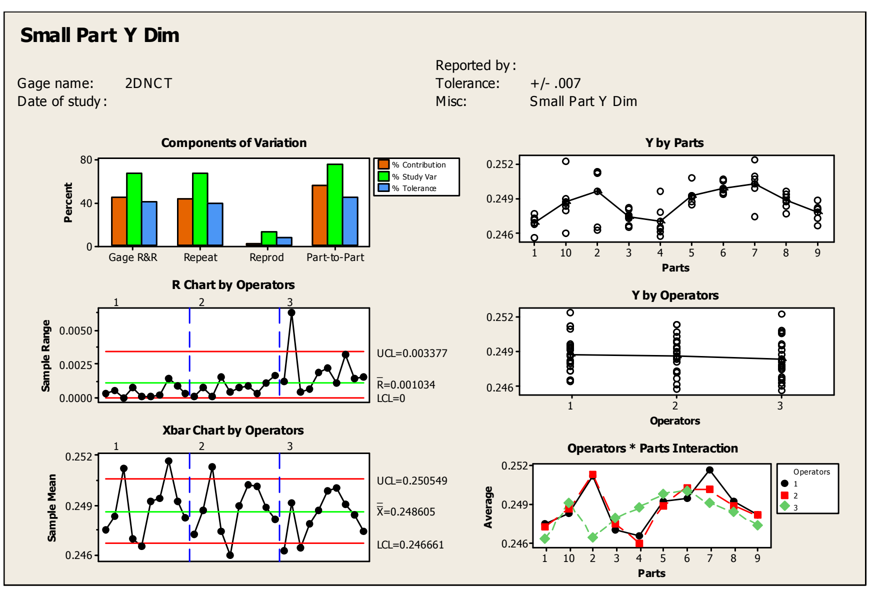
Gage name: 2DNCT
Date of study:
Reported by:
Tolerance: +/- .007
Misc: Small Part Y Dim

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000009	44.61
Repeatability	0.0000008	43.15
Reproducibility	0.0000000	1.46
Part-To-Part	0.0000011	55.39
Total Variation	0.0000019	100.00

Process tolerance = 0.014

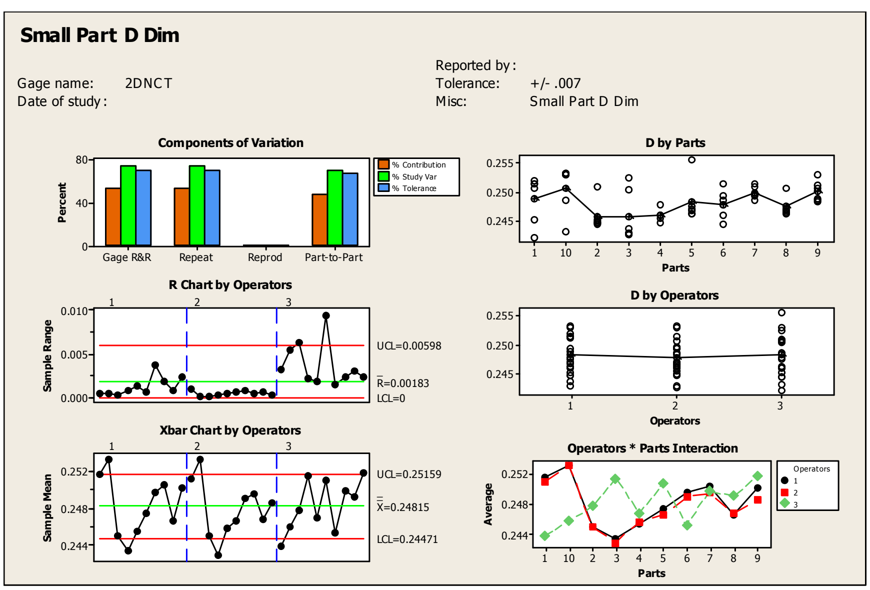
Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.0009318	0.0055907	66.79	39.93
Repeatability	0.0009164	0.0054982	65.69	39.27
Reproducibility	0.0001687	0.0010125	12.10	7.23
Part-To-Part	0.0010383	0.0062296	74.42	44.50
Total Variation	0.0013951	0.0083704	100.00	59.79

Number of Distinct Categories = 1



Gage R&R Results for the Small Paper Part D Dimension

```
Gage R&R for D

Gage name:        2DNCT
Date of study:
Reported by:
Tolerance:        +/- .007
Misc:             Small Part D Dim


                                       %Contribution
Source                   VarComp        (of VarComp)
Total Gage R&R         0.0000026               52.72
  Repeatability        0.0000026               52.72
  Reproducibility      0.0000000                0.00
Part-To-Part           0.0000024               47.28
Total Variation        0.0000050              100.00


Process tolerance = 0.014


                                     Study Var  %Study Var  %Tolerance
Source                 StdDev (SD)    (6 * SD)       (%SV)  (SV/Toler)
Total Gage R&R           0.0016220   0.0097323       72.61       69.52
  Repeatability          0.0016220   0.0097323       72.61       69.52
  Reproducibility        0.0000000   0.0000000        0.00        0.00
Part-To-Part             0.0015362   0.0092170       68.76       65.84
Total Variation          0.0022340   0.0134041      100.00       95.74


Number of Distinct Categories = 1
```



Honest Gage R&R Results for the Small Paper Part

Table D.26

Honest Gage R&R CRR and ICC Results for Small Paper Part

Honest Gage R&R Results	X Dimension Value	Y Dimension Value	D Dimension Value
CRR	36.84	47.37	52.00
ICC	63.15	57.89	48.00
Monitor Class	2 - Acceptable	2 - Acceptable	3 - Acceptable

CAD Overlay Result for the Small Paper Part. Figure D.5 shows the fit of the small paper part with a ±.006 inch tolerance.

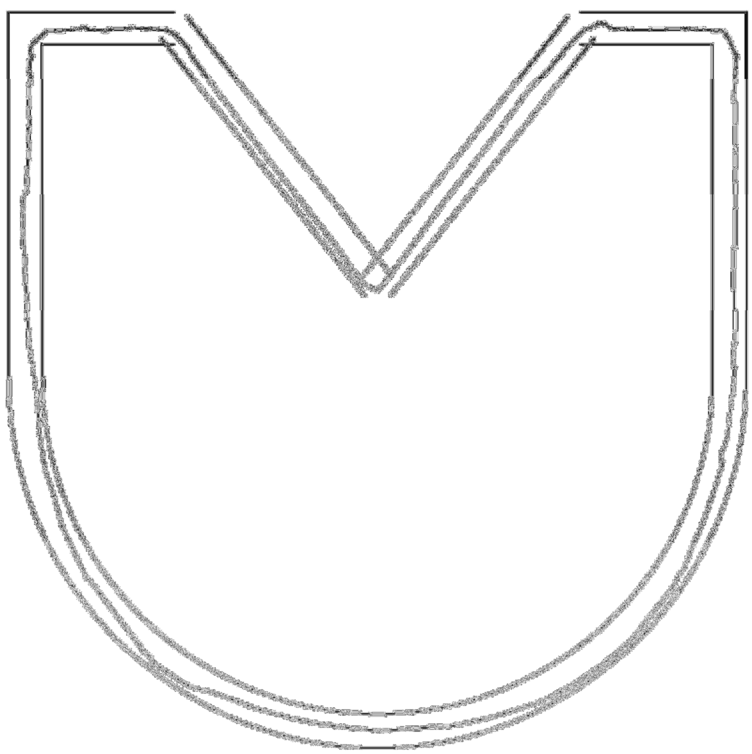


Figure D.5 CAD overlay on the Small Paper Part

AIAG GAGE R&R STUDY DATA AND MINITAB RESULTS FOR THE MICRO PART

Table D.27

2DNCMT AIAG Gage R&R Data for Micro Part

StdOrder	RunOrder	Parts	Operators	D
1	1	1	1	0.08272
2	2	1	2	0.08237
3	3	1	3	0.08220
4	4	2	1	0.08247
5	5	2	2	0.08267
6	6	2	3	0.08268
7	7	3	1	0.08280
8	8	3	2	0.08219
9	9	3	3	0.08260
10	10	4	1	0.08257
11	11	4	2	0.08226
12	12	4	3	0.08271
13	13	5	1	0.08290
14	14	5	2	0.08266
15	15	5	3	0.08286
16	16	6	1	0.08252
17	17	6	2	0.08294
18	18	6	3	0.08188
19	19	7	1	0.08260
20	20	7	2	0.08255
21	21	7	3	0.08246
22	22	8	1	0.08260
23	23	8	2	0.08210
24	24	8	3	0.08286
25	25	9	1	0.08266
26	26	9	2	0.08260
27	27	9	3	0.08291
28	28	10	1	0.08259
29	29	10	2	0.08228
30	30	10	3	0.08206
31	31	1	1	0.08215
32	32	1	2	0.08267
33	33	1	3	0.08294
34	34	2	1	0.08239
35	35	2	2	0.08299

StdOrder	RunOrder	Parts	Operators	D
36	36	2	3	0.08242
37	37	3	1	0.08260
38	38	3	2	0.08276
39	39	3	3	0.08257
40	40	4	1	0.08196
41	41	4	2	0.08282
42	42	4	3	0.08240
43	43	5	1	0.08257
44	44	5	2	0.08244
45	45	5	3	0.08294
46	46	6	1	0.08231
47	47	6	2	0.08241
48	48	6	3	0.08191
49	49	7	1	0.08295
50	50	7	2	0.08258
51	51	7	3	0.08299
52	52	8	1	0.08230
53	53	8	2	0.08268
54	54	8	3	0.08223
55	55	9	1	0.08216
56	56	9	2	0.08195
57	57	9	3	0.08253
58	58	10	1	0.08255
59	59	10	2	0.08216
60	60	10	3	0.08221

Process Capability Results for the Micro Part D Dimension

Table D. 28

Process Capability Results for Micro Part D Dimension

Part	A	B	C	D	E	F	Mean	Range
1	0.08262	0.08226	0.08314	0.08286	0.08293	0.08264	0.0827	0.0009
2	0.08266	0.08273	0.08345	0.08338	0.08348	0.08324	0.0832	0.0008
3	0.08271	0.08293	0.08306	0.08273	0.08294	0.08285	0.0829	0.0003
4	0.08257	0.08271	0.08272	0.08307	0.08319	0.08298	0.0829	0.0006
5	0.08306	0.08299	0.08270	0.08276	0.08293	0.08300	0.0829	0.0004
6	0.08297	0.08323	0.08317	0.08280	0.08255	0.08236	0.0828	0.0009
7	0.08303	0.08286	0.08307	0.08290	0.08237	0.08281	0.0828	0.0007
8	0.08296	0.08231	0.08292	0.08273	0.08280	0.08250	0.0827	0.0007
9	0.08232	0.08253	0.08290	0.08264	0.08255	0.08281	0.0826	0.0006
10	0.08268	0.08279	0.08215	0.08270	0.08250	0.08214	0.0825	0.0006
						Sum	0.8281	0.0065

nominal	tolerance
0.083	0.00080

Xbar =	0.0828
Rbar =	0.0006
Sigma =	0.0003
6-Sigma =	0.0015
USL =	0.0836
LSL =	0.0820
Cp =	1.043
CpU =	1.043
CpL =	1.043
Cpk =	1.043

Measurement Uncertainty Results for the Micro Part D Dimension

Table D. 29

Measurement Uncertainty Results for the Micro Part D Dimension

Specification of Equipment	+/- 0.0008	+/- 0.0008	+/- 0.0008	+/- 0.0008	+/- 0.0008	+/- 0.0008	+/- 0.0008	+/- 0.0008	+/- 0.0008	+/- 0.0008	Summary
Uncertainty of Calibrator (Type B)	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005
Trial	**Part 1**	**Part 2**	**Part 3**	**Part 4**	**Part 5**	**Part 6**	**Part 7**	**Part 8**	**Part 9**	**Part 10**	
A	0.08262	0.08266	0.08271	0.08257	0.08306	0.08297	0.08303	0.08296	0.08232	0.08268	
B	0.08226	0.08273	0.08293	0.08271	0.08299	0.08323	0.08286	0.08231	0.08253	0.08279	
C	0.08314	0.08345	0.08306	0.08272	0.08270	0.08317	0.08307	0.08292	0.08290	0.08215	
D	0.08286	0.08338	0.08273	0.08307	0.08276	0.08280	0.08290	0.08273	0.08264	0.08270	
E	0.08293	0.08348	0.08294	0.08319	0.08293	0.08255	0.08237	0.08280	0.08255	0.08250	
F	0.08264	0.08324	0.08285	0.08298	0.08300	0.08236	0.08281	0.08250	0.08281	0.08214	Statistics
Sum	0.49645	0.49894	0.49722	0.49724	0.49744	0.49708	0.49704	0.49622	0.49575	0.49496	4.96834
Mean	0.08274	0.08316	0.08287	0.08287	0.08291	0.08285	0.08284	0.08270	0.08263	0.08249	0.08281
Maximum Value	0.08314	0.08348	0.08306	0.08319	0.08306	0.08323	0.08307	0.08296	0.08290	0.08279	0.08348
Minimum Value	0.08226	0.08266	0.08271	0.08257	0.08270	0.08236	0.08237	0.08231	0.08232	0.08214	0.08226
Range	0.00088	0.00082	0.00035	0.00062	0.00036	0.00087	0.00070	0.00065	0.00058	0.00065	0.00122
Standard Deviation	0.00031	0.00037	0.00013	0.00024	0.00014	0.00034	0.00025	0.00025	0.00021	0.00029	0.00030
+ 3 Sigma	0.08366	0.08426	0.08327	0.08360	0.08334	0.08388	0.08359	0.08346	0.08325	0.08335	0.08370
- 3 Sigma	0.08183	0.08205	0.08247	0.08215	0.08247	0.08182	0.08209	0.08195	0.08200	0.08164	0.08191
Median	0.08275	0.08331	0.08289	0.08285	0.08296	0.08289	0.08288	0.08277	0.08260	0.08259	0.08293
Uncertainty (Type A)	0.00031	0.00037	0.00013	0.00024	0.00014	0.00034	0.00025	0.00025	0.00021	0.00029	0.00030
Expanded Uncertainty (K=2)	0.00062	0.00074	0.00028	0.00049	0.00030	0.00069	0.00051	0.00051	0.00043	0.00058	0.00060

Dimension D for the micro part is .0829 ± .0006 inches. The reported uncertainty is based on a standards uncertainty multiplied by a coverage factor k=2, proving a level of confidence of 95%.

Table D. 30

Measurement Uncertainty plotting data for Micro Part D Dimension

Description	Part 1	Part 2	Part 3	Part 4	Part 5	Part 6	Part 7	Part 8	Part 9	Part 10
+ 3 Sigma	0.08370	0.08370	0.08370	0.08370	0.08370	0.08370	0.08370	0.08370	0.08370	0.08370
- 3 Sigma	0.08191	0.08191	0.08191	0.08191	0.08191	0.08191	0.08191	0.08191	0.08191	0.08191
.0828+.0006	0.08340	0.08340	0.08340	0.08340	0.08340	0.08340	0.08340	0.08340	0.08340	0.08340
.0828-.0006	0.08220	0.08220	0.08220	0.08220	0.08220	0.08220	0.08220	0.08220	0.08220	0.08220
A	0.08262	0.08266	0.08271	0.08257	0.08306	0.08297	0.08303	0.08296	0.08232	0.08268
B	0.08226	0.08273	0.08293	0.08271	0.08299	0.08323	0.08286	0.08231	0.08253	0.08279
C	0.08314	0.08345	0.08306	0.08272	0.08270	0.08317	0.08307	0.08292	0.08290	0.08215
D	0.08286	0.08338	0.08273	0.08307	0.08276	0.08280	0.08290	0.08273	0.08264	0.08270
E	0.08293	0.08348	0.08294	0.08319	0.08293	0.08255	0.08237	0.08280	0.08255	0.08250
F	0.08264	0.08324	0.08285	0.08298	0.08300	0.08236	0.08281	0.08250	0.08281	0.08214

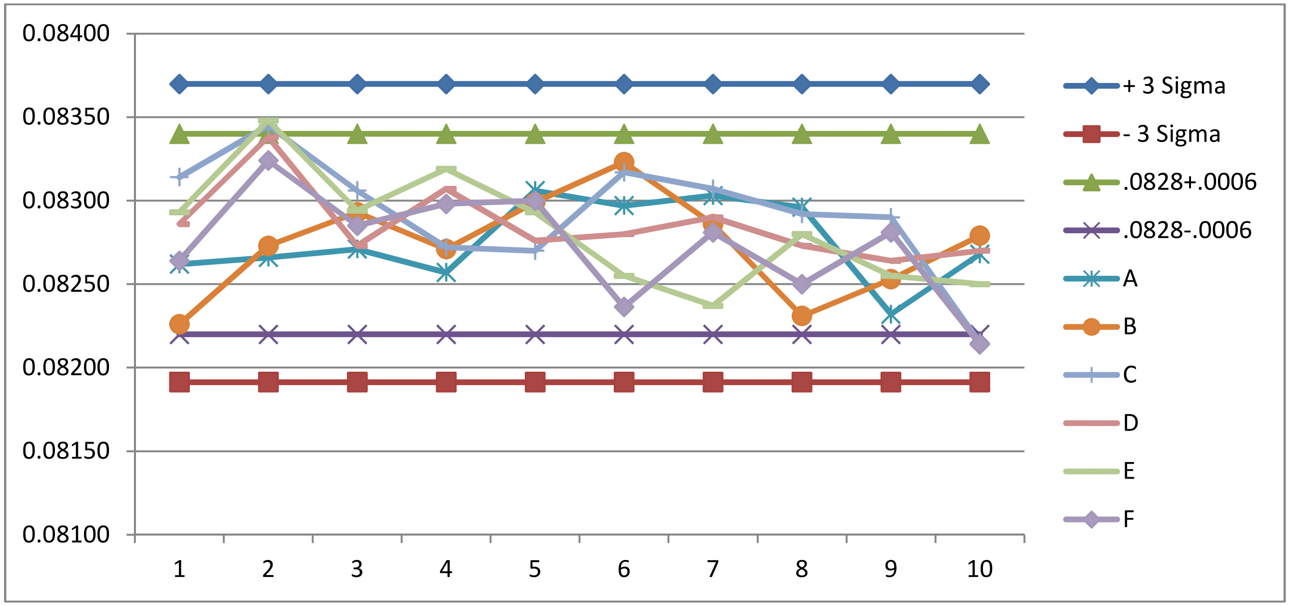


Figure D. 9 Graphic Result for Measurement Uncertainty for Micro Part D dimension

Gage R&R Results for the Micro Part D Dimension

Gage R&R for D

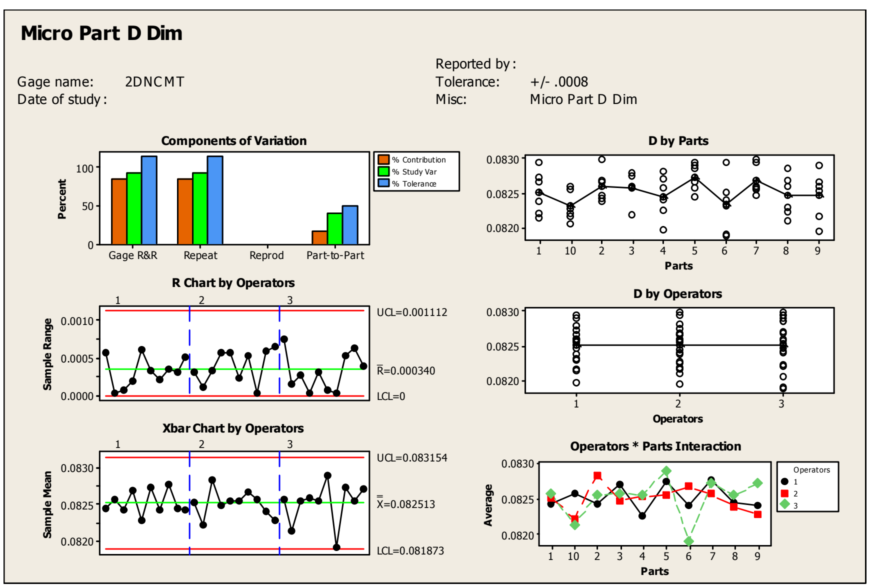
Gage name: 2DNCMT
Date of study:
Reported by:
Tolerance: +/- .0008
Misc: Micro Part D Dim

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000001	83.92
Repeatability	0.0000001	83.92
Reproducibility	0.0000000	0.00
Part-To-Part	0.0000000	16.08
Total Variation	0.0000001	100.00

Process tolerance = 0.0016

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.0003017	0.0018103	91.61	113.14
Repeatability	0.0003017	0.0018103	91.61	113.14
Reproducibility	0.0000000	0.0000000	0.00	0.00
Part-To-Part	0.0001321	0.0007925	40.10	49.53
Total Variation	0.0003294	0.0019761	100.00	123.51

Number of Distinct Categories = 1



Honest Gage R&R Results for the Micro Part

Table D.31

Honest Gage R&R CRR and ICC Results for Micro Part

Honest Gage R&R Results	D Dimension Value
CRR	91.02%
ICC	17.45%
Monitor Class	4 – Don't Use

APPENDIX E

2DNCMT OPERATING PROCEDURE

The 2DNCMT is an extremely flexible machine and can set up to handle parts up to 1-inch in diameter without having to use image stitching, a process where several partial images are combined to create a picture which contains the entire part. The following flowchart defines the process used to perform measurements using the 2DNCMT.

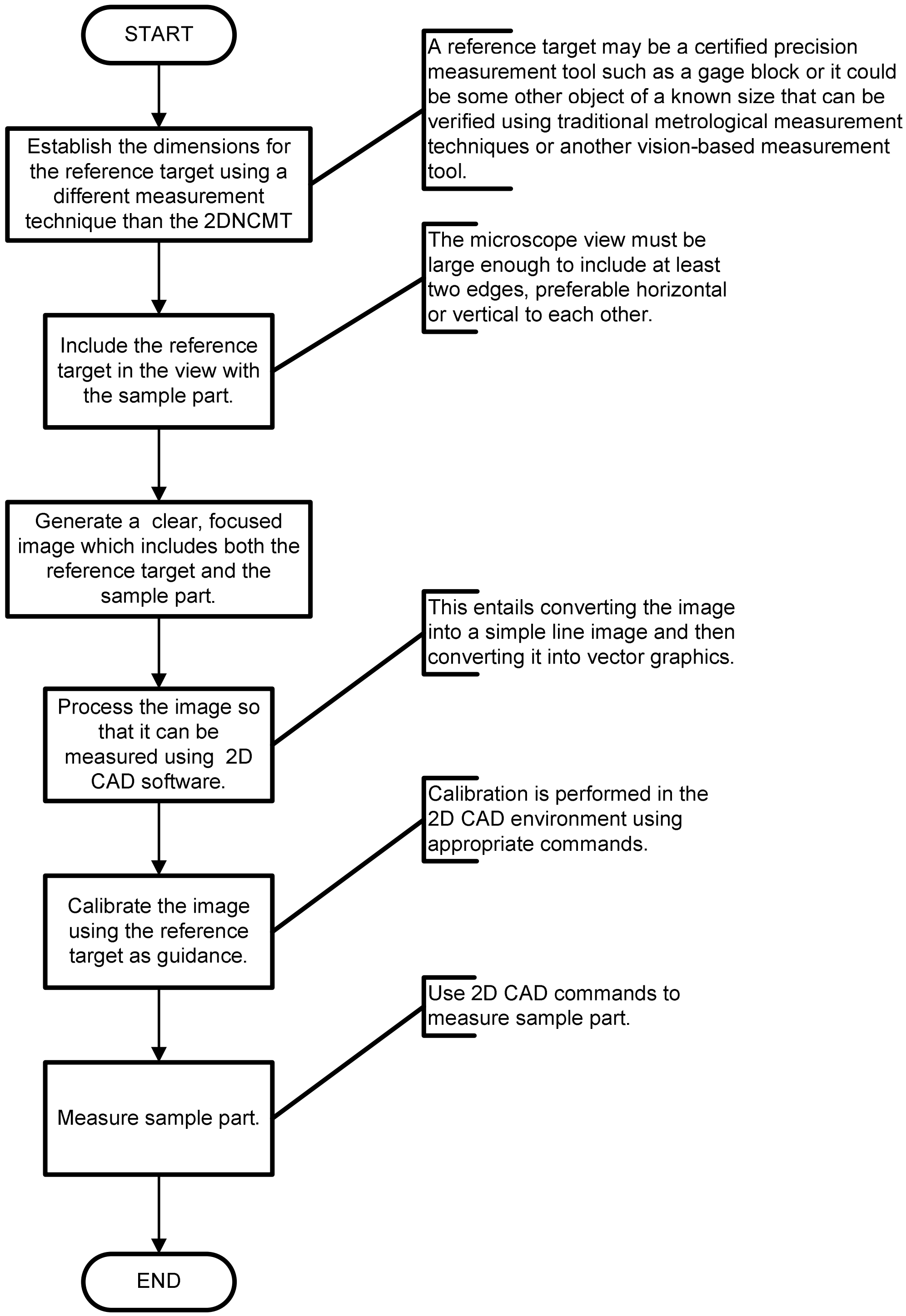


Figure E. 1 2DNCMT Measurement Process
Note: MS-Visio was used to create the flow chart.

2DNCMT SET UP

Figure E.2 shows the 2DNCMT in the basic setup for measuring thing parts.

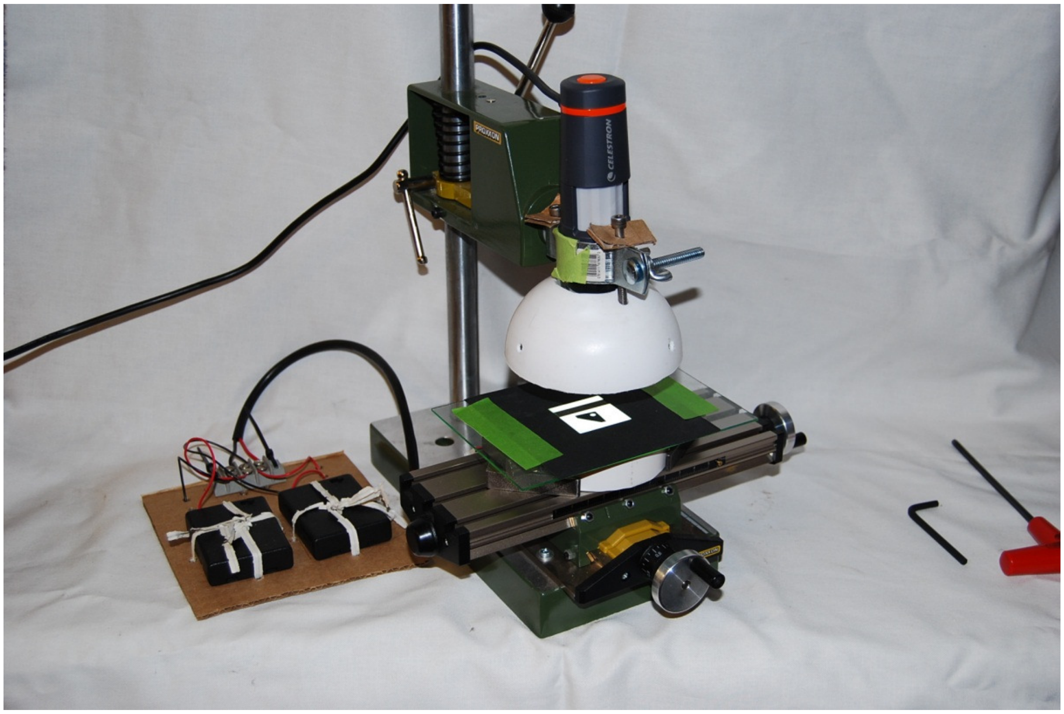


Figure E. 2 Basic 2DNCMT Set Up

2DNCMT OPERATING PROCEDURE

Use the following process to measure a part using the 2DNCMT.

1. Set up the 2DNCMT as shown in Figure E.2.
2. Plug the USB microscope into the computer and start its software.
3. Turn on the lower illumination lighting.
4. Place reference target on the glass platform.
5. Place part on the glass platform.
6. Make sure the part and reference target are close together and centered in the image.
7. Focus the microscope
8. Take image.

9. Open ImageJ
    a. Convert image into binary.
    b. Convert image into edges.
    c. Save converted image.
    d. Exit ImageJ
10. Open Winn TOPO
    a. Open newly converted image
    b. Convert to vectors
    c. Save as a vector file (DXF)
    d. Exit Winn TOPO
11. Open DraftSight
    a. Open vector file
    b. Calibrate reference target in image
    c. Measure the object being examined.
    d. Save file
    e. Exit DraftSight.

APPENDIX F

SOFTWARE ANALYSIS

Table F.1 lists the software that was reviewed for this project.

Table F.0.1

Software Analysis

Software Name	Function	Cost	Comments
Angelscan	3D	free	3D software
David 2.2.5	3D	free	Freeware 3D
Meshlab v121	3D	Free	Open source 3D processing software.
PointCloud	3D	$395	Reverse engineering software
AutoCad R2011	CAD	$3,995.00	Great software but too expensive for this project.
DraftSight	CAD	Free	Autocad clone with limited commands. Works well for project.
Luminance	High Dynamic Range Imaging	Free	HDRI software
Photomatrix Pro	High Dynamic Range Imaging	Free	HDRI software. Watermark in free version. A small fee removes the watermark.
Adobe Illustrator CS5	Image enhancement	$599	Great software but too expensive for this project.
GIMP	Image enhancement	Free	Open source image enhancement software
ImageJ	Image enhancement	Free	Easy to use image enhancement software.
Inkscape	Image enhancement	Free	Good image enhancement software, but could not get DXF conversion options to work consistently.
Photoshop	Image enhancement	$670	Great software but too expensive for this project.
JMathLib	Mathematics	Free	A Matlah clone. Works well for simple computations.
Matlab	Mathematics	Unknown	Great software but too expensive for this project.
Autorace	Raster to SVG	Free	Could not get this software to work.
Plot2SVG	Raster to SVG	Free	SVG formatted files. Need Matlab to run.
Potrace	Raster to SVG	Free	Works in DOS command line mode. Converts to SVG, DXF conversion doesn’t work.
Algolab Photo Vector	Raster to Vector	free	Online service. Tried it a few times, no response.
Image2XAM	Raster to Vector	Free	Like the Ravegrid software it produces images in an impressionist or cubist style.

Software Name	Function	Cost	Comments
PDF2DWG	Raster to Vector	$195	Demo good for 24 translations. Could not get good results from the demo software.
PDF-DXF	Raster to Vector	$180	Limited trial version
pdftodxf	Raster to Vector	Free	Free online service for converting pdf files into DXF format. Tried it a few times, but never got a reply.
R2vtool	Raster to Vector	$58-$99	The demo version was tested. Poor results. No binary conversion, Used skeletonization instead of edge detection.
Ras2Vec	Raster to Vector	Free	Could not get to install properly on computer
RasterVect Free Edition	Raster to Vector	$79.95	Poor translation from raster to vector.
RaveGrid	Raster to Vector	Free	Produced and supported by the Los Alamos Labs. If you like impressionist and cubist art, this is the software for you.
Scan2Cad	Raster to Vector	$249	Excellent software for flatbed scanning or direct conversion raster images and pdf files.
TotalVectorize	Raster to Vector	$39.90	Converts raster images to SVG format
Win TOPO Freeware	Raster to Vector	Free	Used to convert maps to DXF format.
Pixcavator	Shape recognition	Free	Student version is free but limited. Software useful for shape recognition and counting.
DXF2XYZ 2.0	Vector to XYZ	Free	Converts DXF files into xyz coordinates. Can be useful for converting CAD images into G-code.
DXFViewerPro	Viewer	$62	Could not get good results from the demo software

APPENDIX G

MICROSCOPE DESIGN

MICROSCOPES

The inventions of the microscope and the telescope are believed to have happened at the about the same time, around 1600. The first microscope may have been a telescope that was accidentally inverted.

A microscope is an optical instrument that uses a combination of lenses to produce magnified images of small objects, especially of objects too small to be seen by the unaided eye (Planetary Science Institute, 2010). While it is impossible to identify the actual time and place where the microscope was invented, it is known that the concepts of lenses and magnification had existed several centuries before. Rock crystal lenses have been found in Crete and Iraq dating back to 3000BC. Others have been found in Greece, Egypt, and Babylon. Early Romans and Greeks filled glass spheres with water to make lenses. Roger Bacon (1267) promoted water filled glass spheres as reading aids. The first glass lenses were made by monk scribes by cutting a glass sphere in half (Optics 1, 2007).

The earliest microscope, a single lens model, was described as a tube with a lens on one end and a plate for the specimen at the other end. Magnification would have been 6X -10X (Hume, 2010).

Hans and Zaccharias Hanssen (1590s) discovered that by combining, or compounding, different lenses in a tube that the object appeared much larger than with a single lens (Microscope.com, 2011). The Hanssen’s first microscopes, which were the first compound microscopes, were considered toys instead of scientific instruments since their maximum magnification was around 9X and the view was blurry (Vision Engineering, 2011).

Antonie van Leeuwenhoek (1632-1723), also called the Father of the Microscope, is best known for his pioneering work on microscopy design. In 1673 Leeuwenhoek devised a simple method of making lenses without the need of precision grinding methods and produced over 500 optical lenses and designed more than 400 different microscopes (Keeling Lab, 2011). Over time he perfected his lens making techniques and was able to attain “a linear magnifying power of 500 and a resolving power of one-millionth of an inch”. His work was documented in some 200 letters he sent to The Royal Society in London. (Microscope.com, 2011)

THE LIGHT MICROSCOPE

The first light microscope is attributed to Robert Hooke. While Hooke found that Leeuwenhoek’s hand-held single lens microscope design provided clearer images, he also found it difficult to use and strained his eyes. As a result, he devised a compound microscope that sat on a table and used an ingenious method of concentrating light using an oil lamp and a water-filled flask (see figure x.x). In his book, Micrographia, published in 1665, he provided instructions on how to build a compound microscope like the one he used. (Iyer, 2009) (Museum of Microscopy, 2011)

Figure 0.1 Robert Hooke's Light Microscope (Hasseloff, 2011)

In the 1730s Charles Hall found that by using a second lens of a different shape and refracting properties that flint glass appeared to have greater color dispersion than crown glass did at the same magnifications (Davidson, 2003). Almost one hundred years later, Joseph Lister, improved the quality of the objective lens which removed distortions and color change effects, thus finally making the compound microscope a serious research tool (Insley, 2002).

In 1854, the English Society of Arts had a design contest for a simple and affordable student microscope. The contest was won by Robert Field. His design (figure x.x) was widely copied and the basic design is still used today. (Warter, 2011).

Figure 0.2 Robert Field's Student Microscope Design (Warter, 2011)

In 1863, the Ernst Leitz Company introduced the revolving nose or turret with five objective lenses (Microscope.com, 2011). Thirty years later August Kohler invented an illumination system (Kohler Illumination) using double iris diaphragms which produces an illuminated specimen with a bright light and minimum glare (Microscope.com, 2011).

Bausch & Lomb began mass producing microscopes in 1876 and had produced 30,000 by 1900. Their continental model dominated the American microscope scene until after World War II (Warter, 2011).

Figure 0.3 Bausch & Lomb Continental Style Light Microscope (Warter, 2011)

There hasn't been much change to light microscopes over the last one hundred years. The most important advancement has been in the standardization of the parts due to high-volume, low-cost, mass production during the early part of the twentieth century (Hume, 2010). The latest advancement in microscopy has been the introduction of the digital microscope. "Digital microscopes allow for live image transmission to a TV or computer screen and have helped revolutionize microphotography." (Microscope.com, 2011). The days of squinting into an eyepiece are over.

HAND-HELD USB MICROSCOPE

USB microscope is a combination of three very popular high tech gadgets: a microscope, web camera, and a digital camera. It utilizes Universal Serial Bus (USB) technology to power the camera and transmit images to the host personal computer. Many USB microscope capabilities are dependent on the software supplied. Expensive models may come with software that includes image editing, tracing and measuring functions as well. USB microscopes are most useful for viewing two-dimensional objects such as coins, stamps, and printed circuit boards. USB microscopes are advertised as hand-held, but a steady support is needed in order to take a quality image. Magnification is usually overstated and relies on how large the image can be displayed on the computer monitor (USB-Microsope, 2011).

From outward appearances it would seem that most hand-held USB microscopes (Figure G.1) are manufactured under contract by one or two companies as they are very similar in size and function. The outer case may have a rubberized non-slip coating to ensure that the operator can maintain a good grip. The LED illumination and camera optics are recessed inside the case for added protection. Most Low cost USB microscopes use a thumb wheel for controlling focus and zoom.

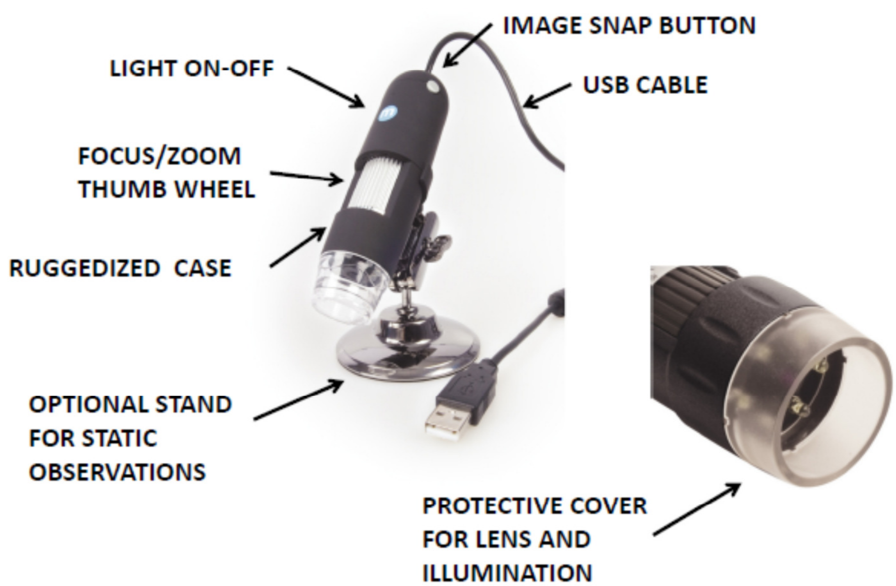


Figure G.1 USB Microscope Features (Generic USB Image)

Table G.1

Parts of a USB Microscope

Name	Description
A/D	Analog-to-Digital (A/D) conversion is used to create appropriate digitized output from the CCD or CMOS for downstream image processing (Carey, 2008).
Camera ASIC	Application Specific Integrated Circuits (ASIC) are used by digital camera manufacturers to provide functions that differentiate their cameras from their competitors. Functions include: vibration or shake reduction, image smoothing, color corrections and compensation, circuitry for digital zoom and focus, and image compression. Recently, manufacturers are starting to utilize programmable digital signal processing (DSP) to replace the custom hard-wired ASICs (Texas Instruments, 2003) (Carey, 2008) (Pentax, 2009) .
DRAM Buffer	A Dynamic Random Access Member (DRAM) buffer is used to temporarily store digital images until they are transmitted to the personal computer.
Firmware Memory	Firmware memory may be Read Only Memory (ROM), Programmable Read Only Memory (PROM) or Erasable Programmable Read Only Memory (EPROM). Firmware for PROM and EPROM is meant to be updated as needed. Firmware is a combination of hardware and software. Integrated circuits (computer chip) that have computer programs or data recorded on them are considered firmware (Apple Support, 2008).
Focus	USB microscopes a thumb wheel and a twin-screw track for focusing. See Section x.x
Image Sensor	The image sensor is either a Charge Coupled Device (CCD) or a Complementary Metal Oxide Semiconductor (CMOS) device.
IR Filter	Infrared (IR) filters are added to digital cameras because CCD and CMOS sensors are very sensitive to near-infrared (IR) light. Although this can be helpful in obtaining the maximum sensitivity, it can also present a few challenges. One shot color cameras, such as DSLRs, must have an IR cut filter. Otherwise the infrared light leaks through the color filters and contaminates the images, producing washed out, poorly balanced and saturated images. IR sensitivity can lead to an unexpected problem with reflections inside the optical instrument (Diffraction Limited, 2011).
LED Lights	The LED lights are used to illuminate the object being examined with the microscope.
Microprocessor	The microprocessor in the USB microscope performs the same

Name	Description
	functions as one found in a personal computer but with a smaller, less complicated operating system. ASICs are also microprocessors, but dedicated to specific tasks.
PC Interface and Power Supply (USB)	A Universal Serial Bus (USB) is used to provide power to the microscope and to transmit image information back to the personal computer.
User Controls	User controls may include an on-off switch for the LED illumination, a snap button to take images while holding the microscope, and a thumbwheel for focusing and zooming (Figure x).
Zoom	USB microscopes a thumb wheel and a twin-screw track for zoom. See Section x.x
Zoom Lens	A zoom lens on a USB microscope utilizes a single lens zoom that is manually controlled by rotating the thumbwheel on the microscope body.

LIGHT MICROSCOPE

The simple light microscope is a manually operated machine that performs the following tasks: Provides a steady or rigid platform for mounting specimens to be observed, a method to focus a set of lenses to magnify the view, and illumination. While light microscopes have improved over the years, the basic anatomy of the machine has not. Figure G.2 identifies the basic parts of a light microscope. Table G.2 provides detailed descriptions of the parts of the light microscope.

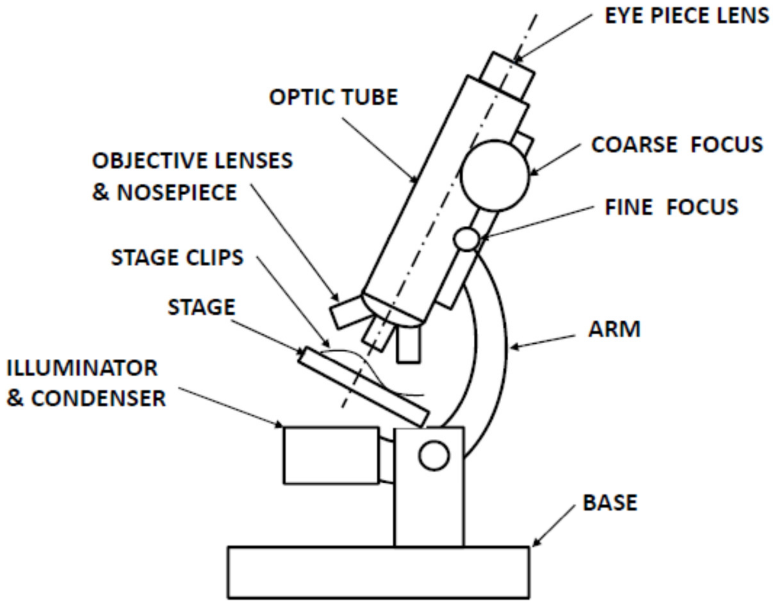


Figure G.2 Parts of a Light Microscope
Note: Redrawn From a Microscope World Image.

Table G.2

Light Microscope Parts

Part Name	Description
Arm	The arm holds the optic tube and connects it to the base.
Base	The base is used to support the microscope structure.
Coarse Focus	The coarse focus is the primary rack-and-pinion gear with a coarse pitch. The knob allows the user to quickly focus the subject.
Eye Piece Lens	The eye piece allows the user to view the specimen. The lens is usually with a magnification power of 10x or 15x. The eyepiece may contain a reticle for measuring objects in view.
Fine Focus	The fine focus is the secondary rack-and-pinion gear with a fine pitch The knob allows the user to fine tune the focus to get more detail.
Illuminator & Condenser	The illuminator is the light source for the microscope. This could be a mirror reflecting ambient light or a powered source. The condenser, or light concentrator, a combination of a lens and iris (aperture) diaphragm, is used to vary the intensity and the size of the cone of light projected upward through a hole in the stage.
Objective Lenses & Nosepiece	The nosepiece (turret) is a rotating collar that holds two or more objective lenses. An objective lens has a set magnification usually 4x, 10x, 40x and 100x powers.
Optic Tube	Maintains a set distance between the eyepiece and objective lenses and also assures the lenses are properly aligned and perpendicular to the stage.
Stage and Stage Clips	The stage is a flat platform where slides are placed. Stage clips hold the slides in place.

APPENDIX H

LIGHTING SYSTEM ANALYSIS

LIGHTING QUALITY

The quality and appropriateness of lighting are critical in designing the 2DNCMT. Understanding illumination types and techniques, geometry, filtering, color, how light interacts with the parts, and a performing a thorough analysis of the inspection environment are important in designing effective vision lighting. Many manufacturers and integrators of machine vision lighting recommend a “rigorous lighting analysis” in order to provide “a consistent, and robust environment, thereby maximizing time, effort, and resources – items better used in other critical aspects of vision system design, testing, and implementation.” (Martin, 2007).

LIGHTING SYSTEM ANALYSIS

Some experts recommend selecting the lighting first in order to reduce design headaches later on. Machine vision lighting is still said to be something of a “black art” and frequently an Integrator will simply select a lighting design and then force it to fit the project. What the camera and vision system need to see is often quite different from what the human observer sees so the lighting must be selected depending on the characteristics of the part being inspected.

Kevin Harding, General Electric (2000) suggested asking the following questions in advance to assure that the right lighting design is used:

- What am I looking for? What specific features on the part are to be inspected? Before starting a clear definition of the task and the application requirement need to be spelled out. If the wrong problem is solved, the application could be seen as a failure.
- What has to be inspected? Have the conditions, requirements, and constraints of the inspection task been defined? Is funding available for the appropriate lighting and camera?
- Can the technique chosen to illuminate the part be performed using the selected equipment? Frequently, the technique and/or the equipment are selected without research.
- Spending the time upfront researching the problem can save a lot of headache later. ”A technique is useless if you can't find the tools to make it work.”

LIGHT STRUCTURE

The way machine vision interprets light is solely a function of how the light interacts with the object. Contrast is created if the object modifies the incoming light in such a way that the outgoing rays are different from the incoming rays. If the object cannot change the incoming light in any way, then the object won't be visible to the camera or the human eye.

The three basic properties that govern the interaction when incident light is shone on a surface: reflection, absorption, and transmission. See Figure H.1. Reflection is incident radiation being reflected by a surface.. Absorption occurs with most surfaces because some incident radiation will always be absorbed. Some incident radiation is always transmitted through the objects that are transparent, translucent, or have through holes.

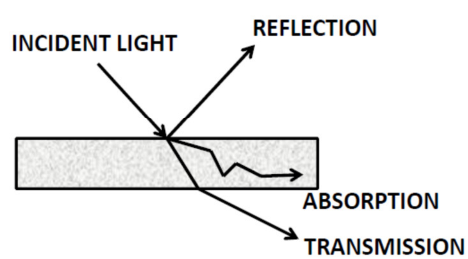
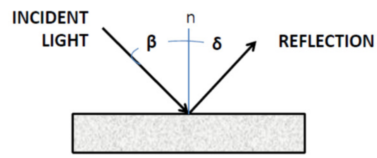


Figure H. 1 Basic Interaction of Incident Light on a Surface

Formulas used for calculating reflectance, absorbance, transmittance, and the RAT formula (conservation of energy) are described in the Table x. Each of these factors is dependent on the wavelength of the incident light and the angle of the light with respect to the object's surface. Information for this table was extracted from: Illumination Structure Solves Multitudes of Applications, Illumination Technologies (2001).

Table H.1

Formulas for describing Incident Radiation

Formula	Description
$Reflectance = \frac{Reflection}{Incident\_Radition}$	Reflectance is the shininess of the object's surface given in a range from 0 to 1 or as a percentage. A surface with 0.9 reflectance is very shiny. If angles β and δ are equal, the reflectance is said to be specular.  *Figure H. 2 Angles of Reflection*
$Absorbance = \frac{Absorption}{Incident\_Radiation}$	Absorbance is also given as a number between 0 and 1 or as a percentage. A material with high absorbance is a piece of black construction paper. Absobance values rarely fall below 5%. Flourescence is a special case of absorbance.
$Transmittance = \frac{Transmission}{Incident\_Radiation}$	Tranmittance is also given as a number between 0 and 1 or as a percentage. An example of a high transmittance material is optical glass. Tranmittance values rarely approach 100% since the clearest of materials have defects and impurities.
$Incident\_Radiation = Reflectance + Absorbance + Transmittance$	The Theory of the Conservation of Energy tells us that total energy in = total energy out.

If there is a strong wavelength dependence for any of these factors, spectral manipulations may be performed by using a combination of light source and filters. Contrast is based on the angle of the incoming incident light is based on the geometry of the lighting fixture. Contrast may be increased or decreased be changing the position of the incident light with respect to the object being inspected.

Light structure is a function of where the incident light originates before affecting the object being inspected. For front lighting, the total range of positions and illumination choices falls inside a hemisphere (see Figure H.3) that is centered over the part.

Illumination can be from a single point, several points, or all points in this sphere. (Ilumination Technologies, 2001)

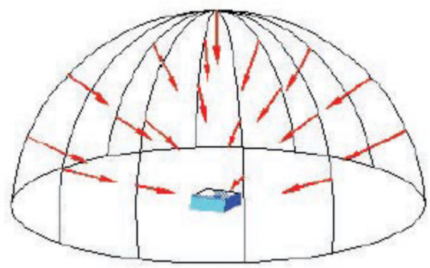


Figure H. 3 Hemisphere of Illumination

Reflective Geometry*.* The way the light strikes the object determines how it will appear to the camera and also how the machine vision software will interpret it. Different illumination methods can produce a significantly different image of the same object. (Stemmer Imaging, 2010) The objective of reflective geometry is to understand where light is going, how it is being reflected into the camera, how to reflect it uniformly, and how to prevent “hot spots” or unwanted reflections (Video Imaging Institute, 2008).

One way of understanding reflection geometry is to visualize a “W”. In Figure H.4 (below), the “W” is seen as the outline between bright field and dark field illumination areas. If the illuminator is placed within the bright field area, the camera will see everything. If the illuminator is placed in the dark field area outside the “W”, the light will never reach the camera (Video Imaging Institute, 2008).

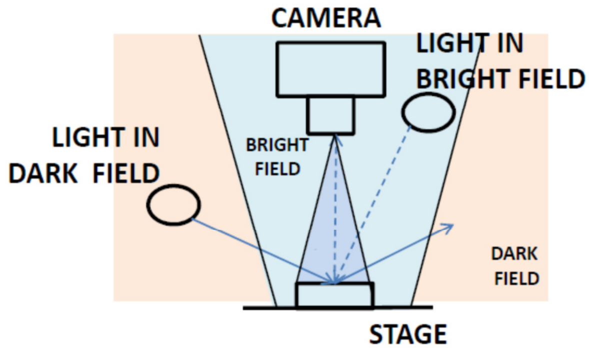


Figure H. 4 Reflection Geometry “W” Test. (Video Imaging Institute, 2008)

Lighting Shapes and Patterns. Some lighting methods used in machine vision are unique. Light lenses that shape light output are used to selectively inspect specific areas on an object while disregarding the rest. Structured lighting, another method of illumination reduces scan time by using narrow beams of light.

Light lenses are designed to not only direct but also shape the light output with even illumination. Light optics come in the following shapes: Narrow which produces a narrow beam of light for long working distances, wide lenses to illuminate large areas, line lenses that produce a thin narrow beam of light, and oval lenses that produce an elongated pattern of light (Smart Vision Lights, 2009).

Structured light is another method for shaping or patterning light for machine vision. It is based on a single camera and a light source which projects a pattern on the surface of an object. By using patterns the machine vision system can more easily identify objects. For example, instead of scanning the entire surface of a cylindrical shape, the machine vision system make look at two narrow beam images to determine that the shape is cylindrical and its size or volume. Conversely, by using patterns, a larger number of data points may be picked off in a single image. (Salvi & Pagés, 2011) Figure H.5 contains examples of pattern and cloud structured lighting (Anon., 2010) (Remondino, 2003).

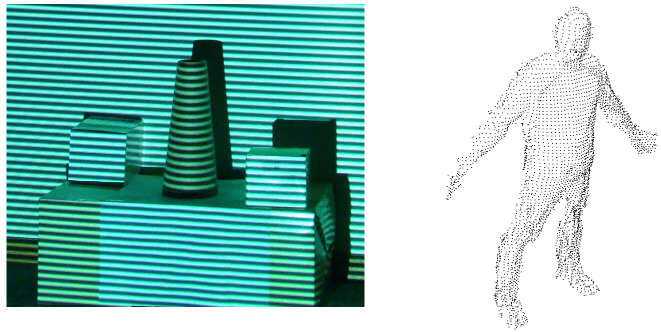


Figure H.5 Examples of Structured Lighting
Left: Pattern Lighting, Right: Point Cloud Lighting.

Light Instability. Light stability, that is the stability of the light reaching the image sensor, is an important consideration when designing machine vision illumination. Causes of light instability include: ambient light, failing or intermittent light sources, and light sources with significant decrease in light output. Ambient light is a primary source of system instability and it originates from overhead factory lighting, sunlight, and light emitted from other work stations. Ambient light can have “tremendous impact on the quality and consistency of inspections”, wreak havoc with maintaining system tolerances, increase downtime, and add additional cost to the system. (National Instrument, 2008) (Martin, 2007) Methods used to reduce light instability, particularly for ambient light include: “high power strobing with short duration pulses, physical enclosures, and pass filters.” IR blockers may also help (Martin, 2007).

Wavelength or Color. Like colors reflect and brighten. Opposing colors absorb and darken. Similarly, materials reflect and/or absorb various wavelengths of light differentially. This effect can be viewed in both color and black-and-white images. In machine vision, colored filters and/or lighting can be used to block or enhance features thus limiting the amount of information in the digital image.

Lighting Types. *According to Microscan, a leader in machine vision lighting equipment, "90% of the success of any machine vision application is through proper lighting. It the camera can't see it, it can't be read or measured." (Microscan, 2011)*

Most lighting is selected by its brightness and spectral quality, but cost, flexibility, longevity, maintenance and stability are also considered important factors. Frequently more than one type of lighting is used to attain the desired effect. Most experts agree that the there isn't one type of lighting that can do everything (National Instrument, 2008).

Several types of lighting are used in machine vision systems: fluorescent, incandescent, quartz halogen – fiber optics, LED - Light Emitting Diode, metal halide (Mercury), xenon, and high pressure sodium (National Instrument, 2008). Other lighting includes ultraviolet (UV) and x-ray.

Filters. Filters are one of the least expensive ways to changes in how an image looks. This was especially true with film photography. With digital photography, photo-editing software has reduced the need for many filters, but they are still used for effects. For machine vision filters are used the same way. The most common filters used with machine vision are the same ones used in photography and for the same reasons: to eliminate unwanted reflection or to accentuate specific features. Ultraviolet (UV), infrared (IR), fluorescence, neutral density, polarizers, and colored lenses are used.

Illumination Effects: Specular and Diffuse Reflections. Specular reflection (also known as direct reflection or glare) is reflection generated in one direction. It is bright, but unreliable. It is unreliable because a small change in the angle between the light source and the object may cause the specular reflection to disappear. In other words, if very precise positioning is not position, do not depend on specular reflections. In diffuse reflection, incoming rays are scattered over a range of outgoing angles so the result is “dim and stable”. The large solid angle of reflection allows the image to be almost constant as the angle changes. Figure H.6 shows the difference between specular and diffuse reflections (CVI Melles Griot, 2009) (Hunter, Biver, & Fuqua, 2007)

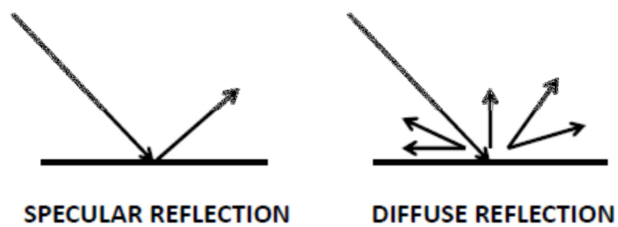


Figure H.6 Reflection Types

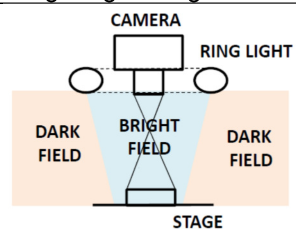
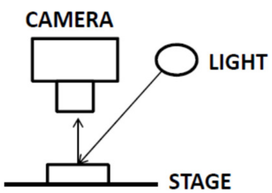
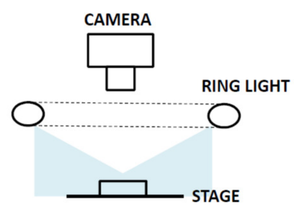
There are simple lighting techniques that can overcome problems with reflections: point-like lighting and diffuse lighting. Point-like lighting is easy to design because it uses small illuminators that can be placed away from the object. Examples of Point-like illuminators are: optical fiber bundles, incandescent lamps, ring lights, and LEDs. All of these produce point-like illumination that create sharp edges, shadows, and accent surface finishes. Diffuse lighting is used to reduce shadows and reduce glare. The trade-off is that diffuse lighting can blur image. Diffuse lighting is also much more difficult and complex than point-like illumination. Diffuse lighting requires that the lens, camera, and stand be mounted around the illuminator (CVI Melles Griot, 2009).

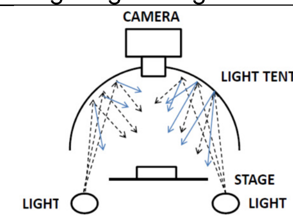
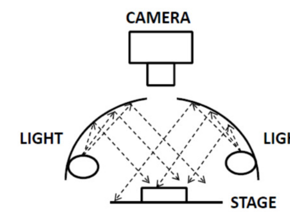
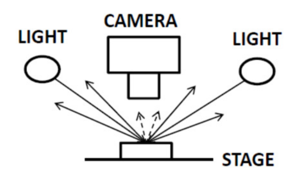
MACHINE VISION ILLUMINATION TECHNIQUES

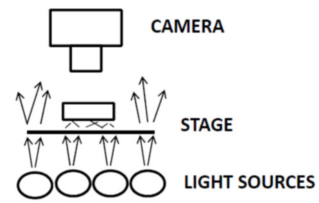
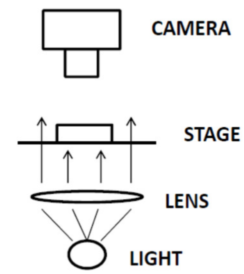
Table H.3 describes common machine vision lighting techniques. The information for this table was extracted from the following sources: Machine Vision Lighting Fundamentals tutorial produced by CVI Melles Griot (2009), A Practical Guide to Machine Vision, National Instrument (2008), and the Light and Optics Reference Guide from the Machine Vision Association of the Society of Manufacturing Engineers (2011).

Table H.3

Selected Lighting Techniques

Illumination	Solid Angle	Direction	Advantages & Disadvantages	Lighting Configuration
Directional Front Illumination using an incandescent or fiber bundle; illuminates objects from top	Point	Front	Advantages : Easy to implement; good for casting shadows Disadvantages: May create unwanted shadows; illumination is uneven.	 *Figure H. 7* Directional Front Illumination
Partial Bright Field	Point	Front or Side	Advantages: good choice for generating contrast and enhancing topographic detail Disadvantages: "hotspot" reflection with on-axis.	 *Figure H. 8* Partial Bright Field
Diffuse Front Illumination using fluorescent lamps; fiber illuminator with diffuser; or incandescent lamp with diffuser; illuminate object from front	Diffuse	Front	Advantages: Soft, relatively non-directional; reduces glare on specular surfaces; relatively easy to implement Disadvantages: Illuminator relatively large; edges of parts may be hazy; low contrast on mono-color parts.	 *Figure H. 9* Diffuse Front Illumination

Illumination	Solid Angle	Direction	Advantages & Disadvantages	Lighting Configuration
Light Tent. Diffuse illuminator surrounds object	Diffuse	Front	Advantages: Eliminates glare; eliminates shadows Disadvantages: Must surround object; Illuminator is large; can be costly.	 *Figure H. 10* Light Tent
Diffuse Dome Illumination	Diffuse	Front	Advantages: very effective at lighting curved, specular surfaces Disadvantages: Require close proximity to the object to be effective.	 *Figure H. 11* Diffuse Dome Illumination
Dark-Field Illumination	Point	Side	Advantages: Illuminates defects; provides high contrast image in some applications Disadvantages: Does not illuminate flat smooth surfaces.	 *Figure H. 12* Dark Field Illumination

Illumination	Solid Angle	Direction	Advantages & Disadvantages	Lighting Configuration
Diffuse Backlighting	Point	Back	Advantages: Easy to implement; creates silhouette of part; very high contrast image; low cost Disadvantages: Edges of objects may be fuzzy; must have space available behind object for illuminator.	 *Figure H. 13* Diffuse Backlighting
Collimated Backlighting	Point or Diffuse	Back	Advantages: Produces sharp images for gaging Disadvantages: Must have space available behind object for illumination	 *Figure H. 14* Collimated Backlighting

Figures H.6 through H.13 in Table H.3 were redrawn for clarification from the following sources: Machine Vision Lighting Fundamentals tutorial produced by CVI Melles Griot (2009), A Practical Guide to Machine Vision, National Instrument (2008), and the Light and Optics Reference Guide from the Machine Vision Association of the Society of Manufacturing Engineers (2011).

BRIGHTNESS AND CONTRAST

Contrast is defined as "the amount of color or grayscale differentiation that exist between various image features. Image having a higher contrast level generally display a greater degree or color or grayscale variation than those of lower contrast." Figure H.14 is an example of high contrast.

Figure H. 15 Contrast Example

ILLUMINATION PROBLEMS

Stray light, contrast, shadows, and noise can all produce poor images that are not worth using. In this section, solutions for dealing with these problems are discussed.

Stray Light. Stray light is light that is not supposed to be in the optical system. Stray light can obliterate important features in an image, cause discolorations. Some causes of stray light are: light leaks through the view finder or body of the camera, irregular reflections, ghosting due to diffraction, and lens flare. Figure H.15 is an example of how stray light infiltrates the optical system.

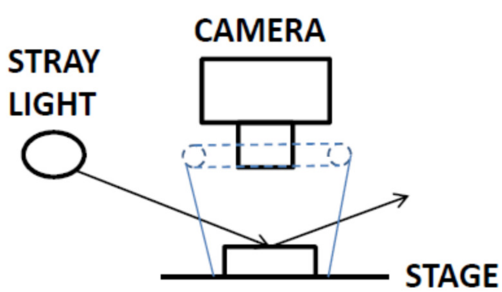


Figure H. 16 Stray Light

“Lens flare is caused by non-image light which does not pass (refract) directly along its intended path, but instead *reflects* internally on lens elements any number of times (back and forth) before finally reaching the film or digital sensor.” (Cambridge In Colour, 2011)

The solution is to prevent stray light from getting into the image. One solution used in this project was by using rings made from black cardstock.

Shadows. Two methods were found to reduce shadows. The first was to place the object being examined on black paper. The second was to use spherical illumination to create indirect lighting. The indirect light fills in the shadows.

Contrast

Backlighting the object being examined and using a ring to block stray light was the best method.

Noise. In many cases, using image enhancement software was to only way to blot out noise. In other cases, painting the objectionable surface with Dye-Chem worked well.

Glare and Light Leakage. In photography, glare and light leakage can be reduced or eliminated by using lens covers, diffusion boxes or tents; or by performing the photographic work in a controlled environment. In this project, the following methods were tested.

- Colored rings surrounding object being imaged
- Blocking the USB microscope’s integrated illumination

FINAL LOWER ILLUMINATION DESIGN

Back lighting and color play an important part in noncontact 2D measurement systems. The light box for this project has the following requirements:

- The lighting must be adjustable in order to achieve the best edge definition.

- Depending on the material of the object being measured, different color backgrounds, i.e. red, green, and blue enhance edge definition.

Light Emitting Diodes (LED) were selected for this project for the following reasons:

1. Size. Miniature LEDs take up minimum space.
2. No heat. LEDs will not add heat to the box, calibration fixture, or object being examined like incandescent light bulbs will do.
3. Power consumption. A requirement of the project is that the hardware be portable with the only connection being the USB cable to a personal computer.

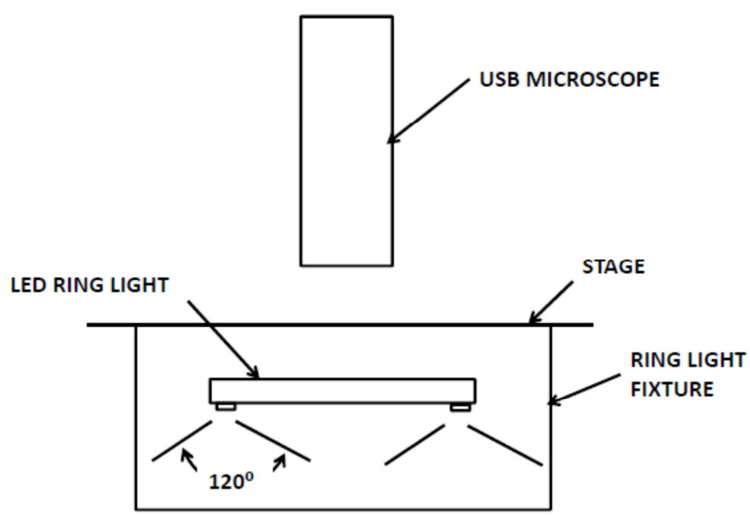


Figure H.17 Inverted Lower Ring Light

FINAL UPPER ILLUMINATION DESIGN

Upper illumination is designed for producing high contrast and eliminating shadows. Two designs were developed: direct illumination (Figure H.18) and a spherical diffuser (Figure H.19). LEDs were used for the same reasons as in the Lower Illumination design.

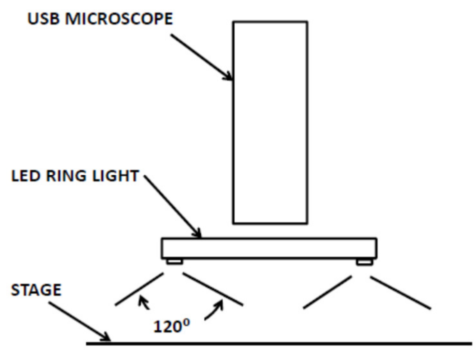


Figure H. 18 Direct Upper Illumination

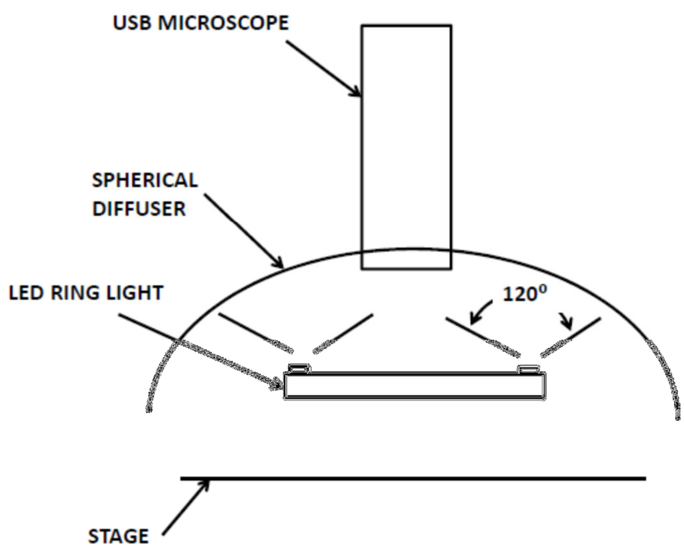


Figure H. 19 Spherical Diffuser

APPENDIX J

IMAGE ANALYSIS AND HISTOGRAM STUDY

OVER OR UNDER EXPOSURE

Histograms provide a graphical representation of a distribution of digital image data. For digital images it can be used to gain information about the image. There is no such thing as a correct histogram. It can only provide information on whether an image is under or overexposed. The following rules apply to digital image histograms (McAndrew, 2004, pp. 70-81):

- In a dark image, the gray levels are shifted toward the left (dark end) of the scale.
- In a bright image, the gray levels are shifted toward the right (light end) of the scale.
- A well contrasted image has the gray levels well spread out across the range.

In photography an image that is too dark or too light is considered to be poorly contrasted. A histogram (Figure J.1) is a useful method of analysis is to determine if there is a significant difference of separation between the object and the background. This is easily identifiable in histogram is there is a noticeable threshold (dip or valley in the histogram), that places all pixels above a certain brightness are maximized to some maximum value, likewise, pixels below the threshold are minimized to some minimum level. An image's then the image is a good candidate for the project (TechTalk, 2011).

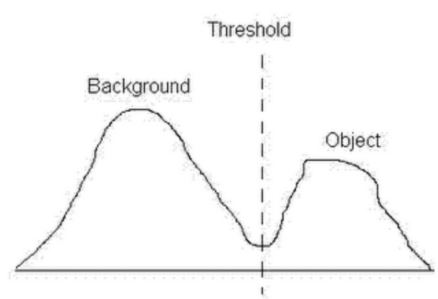


Figure J. 1 Histogram Example

Table J.0.1

Histogram Examples

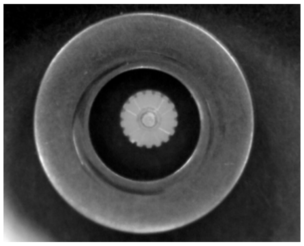
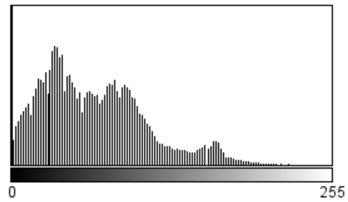
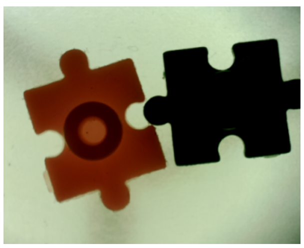
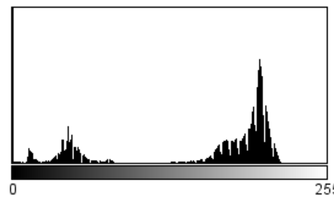
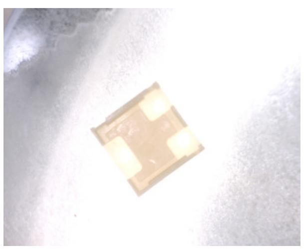
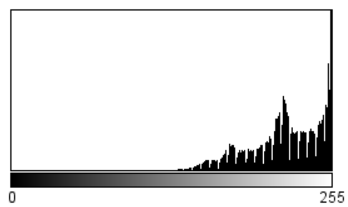
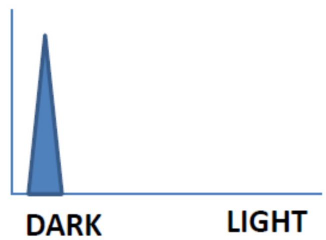
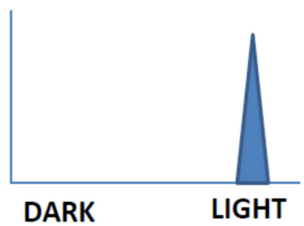
Image	Histogram	Description
		Not only is this image too dark, the gray levels are spread out. t
		This image has a good separation between bright and dark. This makes this image a good candidate for measurement.
		An over exposed image is just as poor quality as one that is too dark. p ixel values are 'clustered' Overexposure increases noise in the image. It also hides important edges.

Table J.0.2

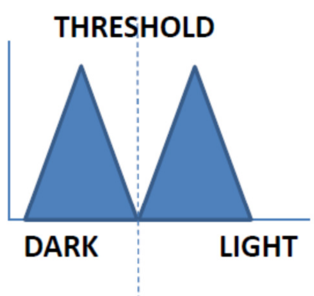
Histogram Analysis Table

<table>
<tr><th>Histogram Shape</th><th>Description</th></tr>
<tr><td>
</td><td>

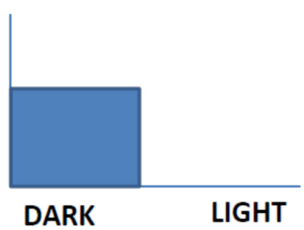
- Pixel values are ‘clustered’ to the left end of the histogram. If the cluster is all black, image detail has been lost or “blocked up.”
- No defined threshold
- Too little contrast
- The image is underexposed (too dark).
- Increased noise
- Poor edge detection

</td></tr>
<tr><td>
</td><td>

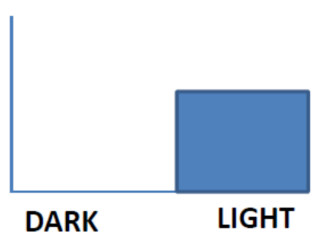
- Pixel values are ‘clustered’ to the right end of the histogram. If the cluster is all black, image detail has been “washed out.”
- No defined threshold
- Too much contrast
- The image is overexposed (too bright).
- Increased noise
- Poor edge detection

</td></tr>
<tr><td>
</td><td>

- This image has a good separation between bright and dark. This makes this image a good candidate for measurement.
- Bright and dark pixel values are easily identified.
- Threshold between light and dark defined
- Good contrast between object and background
- Correct image exposure
- Low noise
- Excellent edge detection

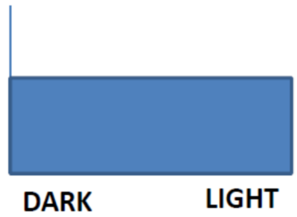
</td></tr>
<tr><td>
</td><td>

- Pixels are shifted to the left end of histogram, but are spread out.

</td></tr>
<tr><td>
</td><td>

- Pixels are shifted to the right end of histogram, but are spread out.

</td></tr>
</table>

Histogram Shape	Description
	• Stretched or “combed” • Tones redistributed over larger area • Some tones are missing • Risks posterization

TEST DATA

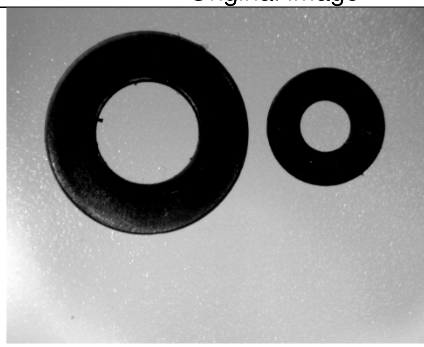
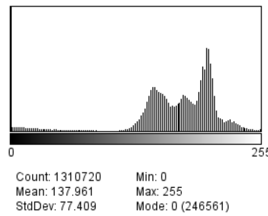
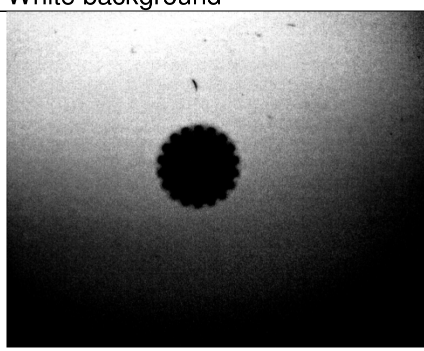
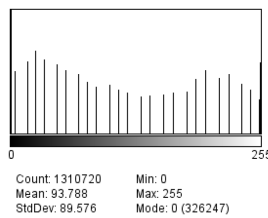
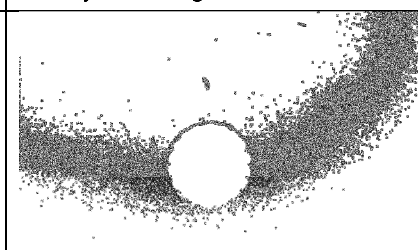
All tests were performed using ImageJ image enhancement software.

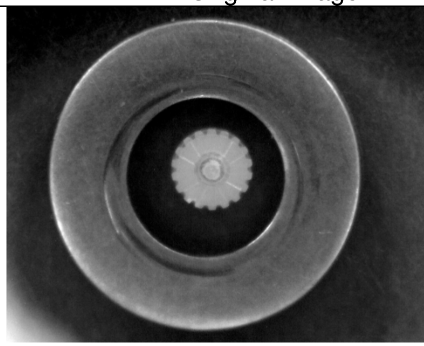
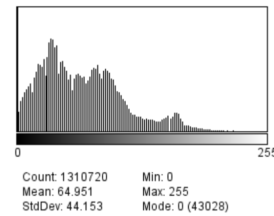
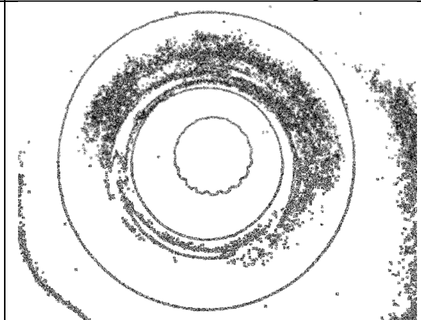
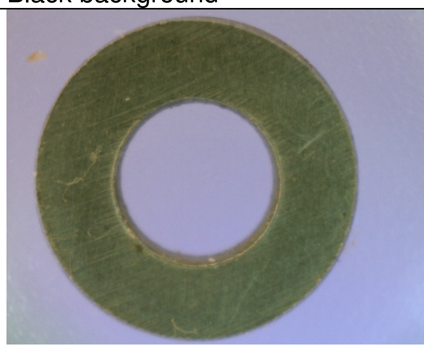
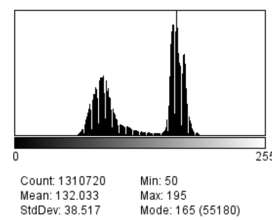
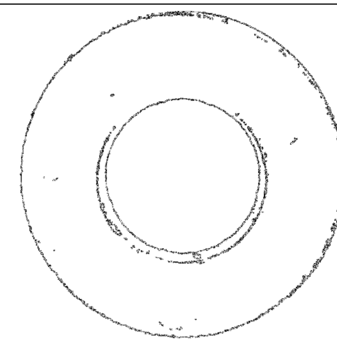
Process used:

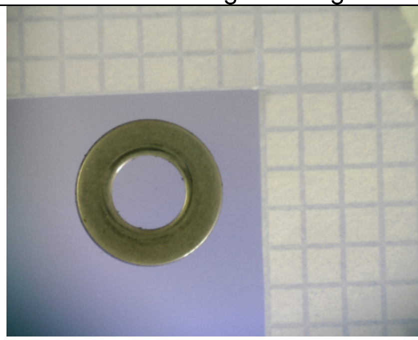
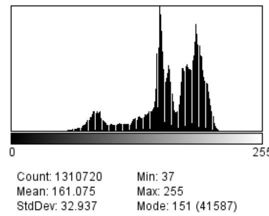
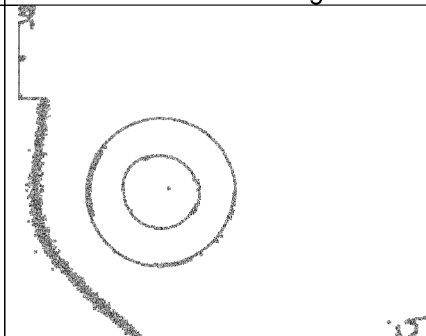
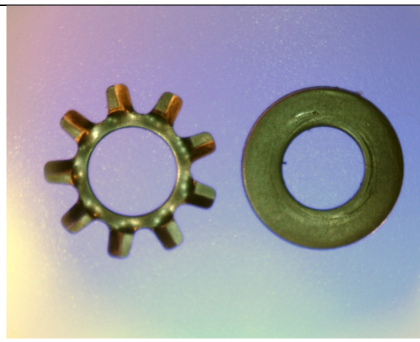
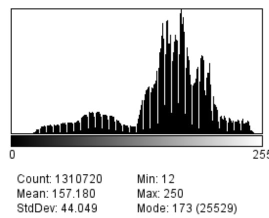
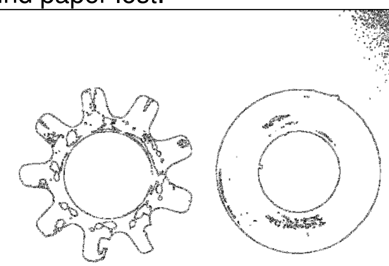
1. Analyze > Histogram
2. Process > Binary > Make Binary
3. Process > Find Edges

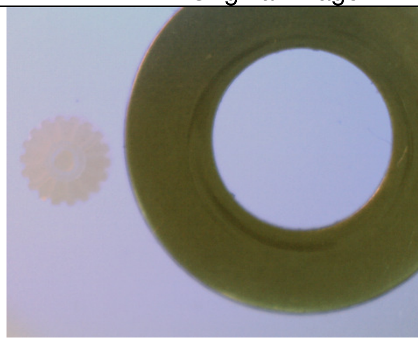
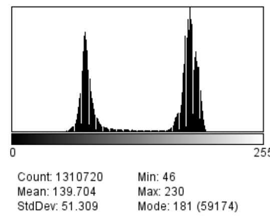
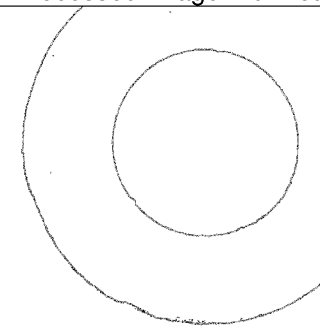
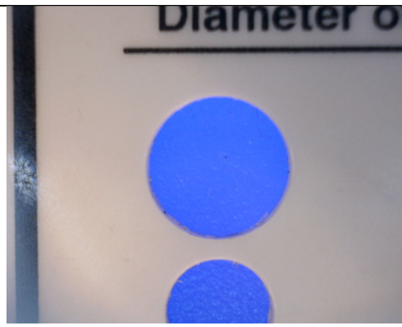
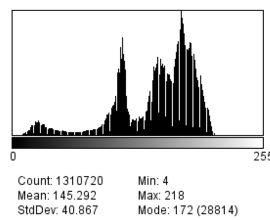
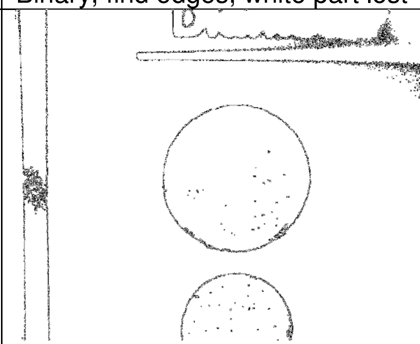
Table J.0.3

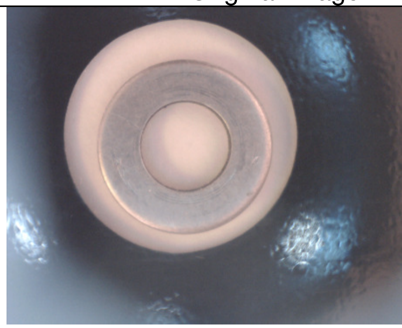
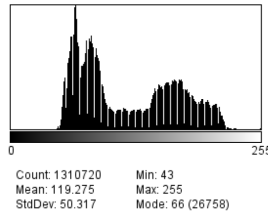
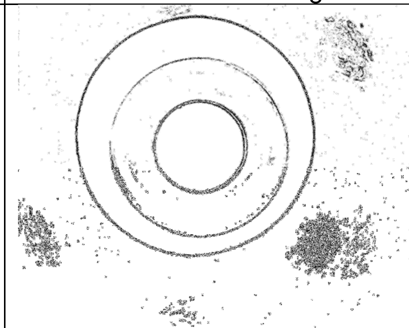
Image Analysis Data

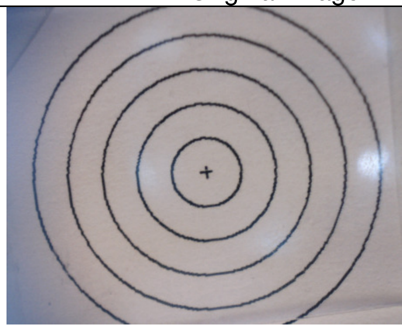
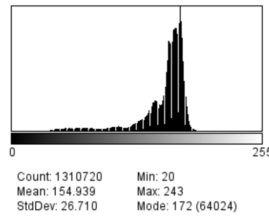
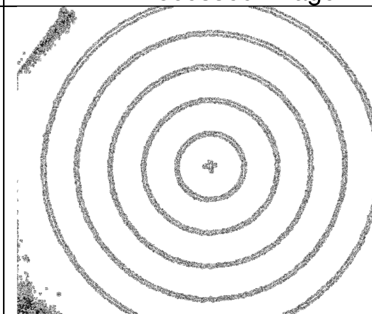
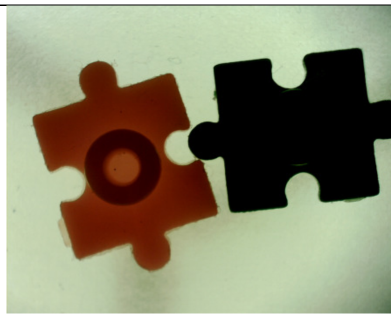
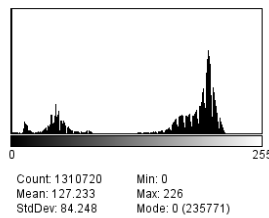
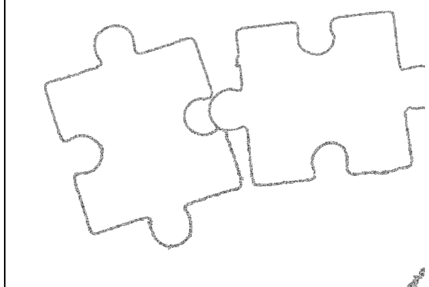
#	Original image	Histogram	Processed Image with notes
1	 White background		 Binary, find edges
2	 White background		 Binary, find edges

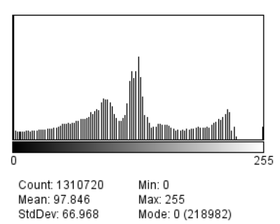
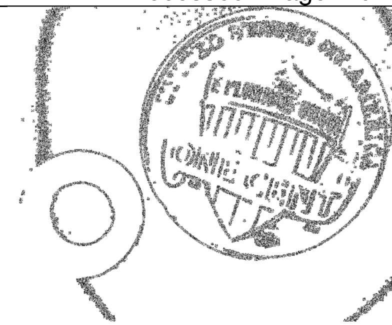
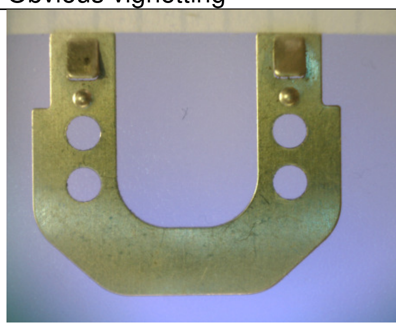
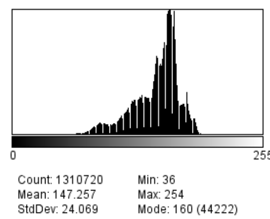
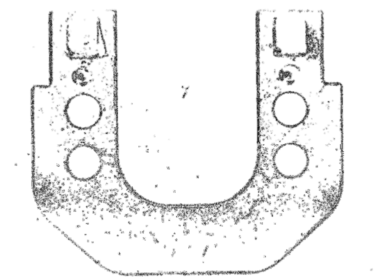
#	Original image	Histogram	Processed Image with notes
3	 Black background		 Binary, find edges
4	 Blue background		 Binary, find edges

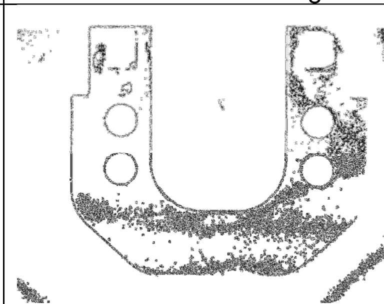
#	Original image	Histogram	Processed Image with notes
5	 Blue background		 Binary, find edges Grid paper lost.
6	 Blue background		 Binary, find edges

#	Original image	Histogram	Processed Image with notes
7	 White part on blue background		 Binary, find edges, white part lost
8	 Blue background		 Binary, find edges

#	Original image	Histogram	Processed Image with notes
9	 Black vinyl background, glare	 	 Find edges, Binary  Binary, Find edges

#	Original image	Histogram	Processed Image with notes
10	 Printed object, white paper, glare		 Binary, find edges. Edge detection outlines circles
11	 Yellow background, red and green objects.		 Binary, find edges

#	Original image	Histogram	Processed Image with notes
12	 White background Obvious vignetting		 Binary, edge finding
13	 Blue background, glare		 Find edges, binary Poor outline, noise

#	Original image	Histogram	Processed Image with notes
			 Binary, find edges Poor outline, noise

APPENDIX K

DIFFERENCES BETWEEN CCD AND CMOS SENSORS

Table K.1 describes a few selected, but important, differences between CCD and CMOS technology. Data for the Table was extracted from the following sources: CCD vs CMOS: Facts and Fiction (Litwiller, 2001) and An Introduction to CMOS Image Sensor Technology (Silicon Imaging, 2011).

Table K.0.1

CCD - CMOS Comparison

Feature	CCD	CMOS
Anti-Blooming	CCDs need specific engineering for anti-blooming*. * Anti-Blooming. The ability to gracefully drain localized overexposure without compromising the rest of the image in the sensor	CMOS sensors have immunity to blooming.
Applications	Photography and high definition tasks	Toys, cell phone cameras, bar code systems, PC video conferencing
Image Quality	High	Low
Integration	CCDs require external clocks and inputs which limits their use to discrete systems.	CMOS sensors use the same manufacturing processes as memory and microprocessors. CMOS sensors can also be integrated with these components on a single piece of silicon.
Integration Method	most functions take place on the camera's printed circuit board	converts charge to voltage at the pixel, and most functions are integrated into the chip
Manufacturing Cost	CCD	CMOS imagers are manufactured in the same process as memories, processors and other high-volume semiconductor devices.
Physical Size	Large	Small
Pixel Addressability	Transfer pixel values are moved in "buckets" which means that the individual pixel values on the CCD cannot be read individually.	Each pixel on a CMOS sensor has a unique location on an x-y grid. This allows the pixels to be read individually.

Feature	CCD	CMOS
Power Consumption	CCDs are inherently power hungry.	Low power use.
Shuttering	CCDs have the ability to start and stop exposure arbitrarily.	Shuttering with CMOS sensors is accommodated by using one of the following methods: • A rolling shutter, exposes different lines of the array at different times. • A uniform synchronous shutter, sometimes called a nonrolling shutter, exposes all pixels in the array at the same time.
Speed	Most consumer devices do not require high speeds. Some commercial CCDs are designed for speed.	CMOS is quicker because all the camera functions are part of the image sensor.
Windowing	CCDs have limited windowing capability due to poor pixel addressability.	Because the pixels on CMOS device are fixed, these sensors can perform windowing functions such as sampling a portion of the image, anti-jittering, motion tracking and other advanced imaging techniques.

APPENDIX L

FEASIBILITY STUDIES AND RESULTS

The two feasibility studies were performed prior to starting this thesis project. The first experiment was similar to one performed by Kee and Ratnam (2009) using a flatbed scanner. Kee and Ratnam's experiement involoved measuring fine electrical wires. The experiment provided proof that Kee and Ratnam's conjecture that inexpensive off-the-shelf technology could perform almost as well as expensive dedicated metrology equipment.

The second experiment used an inexpensive USB microscope.The flatbed scanner in the first experiment produced images that were almost 1:1 so measuring was easy, but microscopes magnify objects and every time the USB microscope was refocused, the magnification could change slightly. Early research showed that including a grid or scale in the image made it easy to measure the object. In this experiment calipers set at a specific measurement were laid on top of a piece of grid paper. The grid lines were used to detemine width between the caliper jaws. The number of grids in the image determined the scale. This method worked well, but was not very accurate. This experiment; however, proved that the measurement algorithms used by manufacturers of vision-based measurement systems were not as proprietary as one would think.

FEASIBILITY STUDY #1: 2D FLATBED SCANNING

An exploratory experiment was devised using 2D flatbed scanning equipment. The sole purpose for Experiment #1 was to learn how to process digital images into a format in which the data could be accurately measured. The test devised was similar to the one performed by Kee and Ratnam (2009) for measuring fine electrical wires.

Objective. The objective of the experiment was to generate a digital image of an object and devise a method for accurately measuring it. Kee and Ratnam's paper included the process they used for converting scanned images into measureable graphics, but did not include the algorithm they used for converting pixels to micrometers (µm).

Specimen Selection. The specimen selected to be measured for the first experiment was a brass locknut (Figure x) randomly selected from a tub of miscellaneous hardware.

Hardware and Software Used

Flatbed Scanner: HP 5200C color scanner, manufacture date: 7/2007

- Optical Resolution: 600.0 dpi x 1200.0 dpi
- Scan Element Type: CCD
- Software: HP ScanJet

Image Processing Software:

- Microsoft Office 2010
- *Matlab Student r2010a*
- *Adobe Illustrator CS5*
- AutoCad Student 2011

Experiment Equipment:

- Quilter's Scale
- Lock Nut

Procedure. Feasibility Study #1 was extremely elementary, but necessary in order to understand the process how digital images could be used to measure objects. The following steps were performed:

- Scan the specimen using a flatbed scanner.
    - The nut is covered with black paper to blur shadows.

- The quilter’s square is used to align the specimen and to supply a grid.

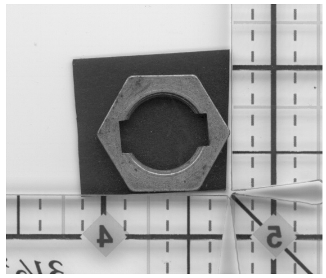


Figure L. 1 2D Flatbed scanner setup

- Crop image to 300 x 300 pixels

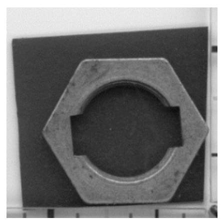


Figure L. 2 Cropped image of lock nut

- Apply edge detection algorithms and select the best image.
    - Software: Matlab

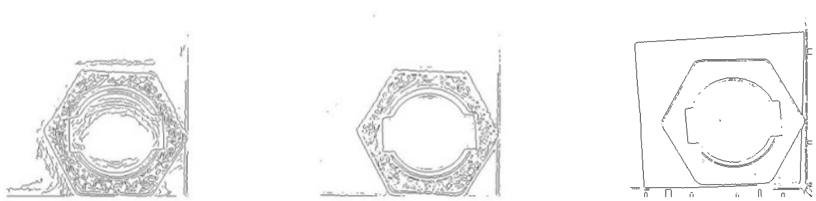


Figure L. 3 Edge Detection Algorithm Results: Left: Canny, Middle: Zero Cross, and right: Sobel.

- Vectorize image
    - Software: Adobe Illustrator CS5

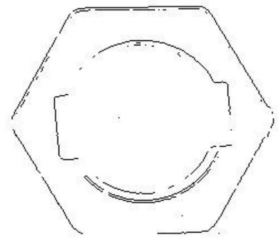


Figure L. 4 Vectorized image of lock nut

- Scale image in CAD
    - Software: AutoCad R2010
    - Set 1 inch = 300 pixels

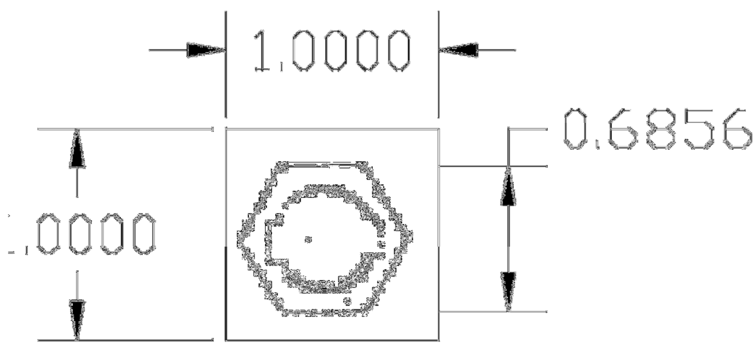


Figure L. 5 Image measured in CAD

- Manually Verify

    Use dial calipers to measure part. The part measured 0.692 inches

    The scanned image measured 0.6856 inches

    The difference was 0.0064

Feasibility Study #1: Analysis

- Feasibility Study #1 assumed that the flatbed scanner was 1:1, but it wasn't. A scaling method needed to be derived in order to accurately measure parts.

- Subsequent flatbed scanner experiments were run using a different scanner and a micro gear.

- The second experiment was run using a different scanner, a Canon 9000F. This scanner was also not 1:1.

- A third experiment was run on a Canon 9000F flatbed scanner using a micro gear (less than 0.1 inch diameter) provided in a sample pack from Accumold Corporation as a test part The flatbed scanner's image resolution was not adequate to produce a usable image.

- Other problems with the flatbed scanners included: heavy shadowing and huge file sizes.

FEASIBILITY STUDY #2: USB MICROSCOPE

It became apparent in Feasibility Study #1 that, while flatbed scanners were great at scanning, they were really only good for scanning very thin objects such as sheets of paper and sheet metal parts, and not good for imaging parts less than 0.25 inches in diameter.

Object Selection. The specimen selected to be measured for the Feasibility Study 2 was calipers on grid paper.

Grid Sele**ction.** Two variations of grids were used, the first was a sheet of vellum with a pre-printed 0.1-inch grid and the other was a checkerboard design generated using Microsoft Powerpoint, as seen in Figure 5.6.

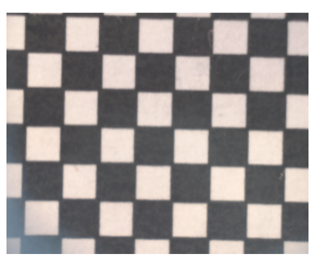


Figure L. 6 Checkerboard design generated using Microsoft Powerpoint.

Hardware and Software Used

USB Microscope

- USB Microscope Model: Carson 44302

- Software: Miscroscope Suite 2.0 (included with the USB microscope)

Image Processing Software:

- Matlab Student r2010a
- Adobe Illustrator CS5
- AutoCad Student 2011

Experiment Equipment

- Vellum grid paper with 0.1” x 0.1” grid
- Brown & Sharpe dial calipers

Procedure. The experiment was designed to provide an understanding of how digital images could be used to measure objects. Several experiments were run in order to get a “feel” for the process. Figure L.7 shows an example image for Feasibility Study #2.

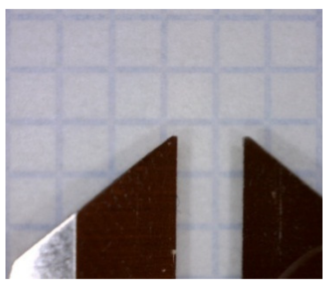


Figure L. 7 Caliper measuring

In this example the caliper tips were set to 0.120. After scanning, the image was cropped so that a grid of 6x5 was displayed. Each grid is 0.1 x 0.1 inches so the image was 0.6 x 0.5 inches. The pixel size of the image was 1280x1024 pixels. The following steps were taken to attain an accurate measurement.

1. Scan Part using USB Microscope
   - The calipers are lying on a sheet of vellum with a pre-printed grid of 0.1 inch.

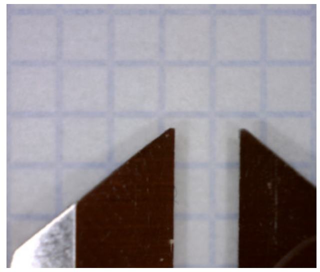


Figure L. 8 Caliper image

1. Apply detection algorithms and select the best image.
2. Vectorize image.
3. Scale image in AutoCad by setting the alternate units so that 1-inch = 1280 pixels (1/1280 = .0007813).

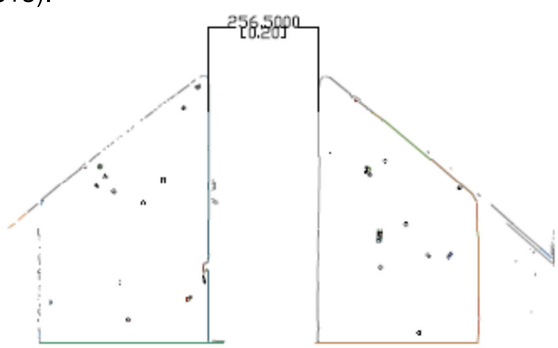


Figure L. 9 Caliper image imported into AutoCad and dimensioned.

Feasibility Study #2: Analysis. Like in Feasibility Study #1, the USB microscope was not producing an accurately dimensioned drawing. A scaling algorithm was needed.

CONCLUSIONS REACHED FROM THE FEASBILBITY STUDIES

Feasibility studies #1 and #2 took place before considering the cost of the software. The cost was way too high for someone looking for a low-cost solution. The software for the project, if purchased new, would cost nearly $4000 (Matlab, Adobe Illustrator, and AutoCad). See Appendix F. Software Analysis for details. The project would have to be completely re-thought.

The Hints and Tips section of the Scan2CAD website (Softcover, 2011) was helpful for providing tips for using a flatbed scanner to generate images of 3D objects. The Scan2CAD software would have been an excellent choice for this project, but it cost too much.

The Kee and Ratman experiment relied heavily on Matlab® for digital image processing, particularly for edge detection algorithms.

Feasibility Study #2 was repeated with the same success using the following objects as shown in Figure L.10.

(a) (b) (c)

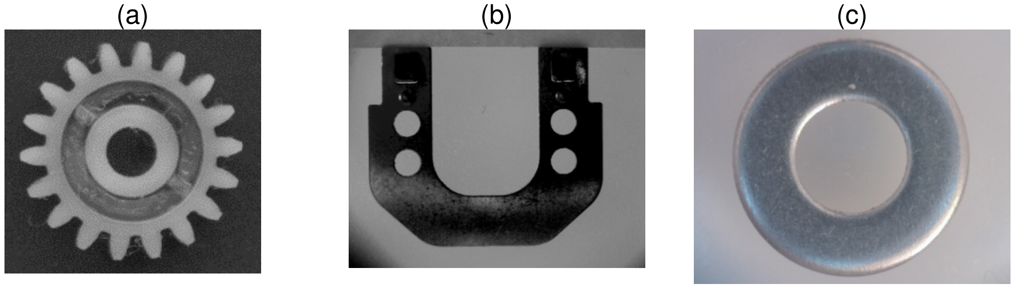


Figure L. 10 Sample Parts used in Experiment #2
Parts are as follows: (a) Spur gear from a battery powered hand drill, (b) an electrical jumper part, (c) a flat washer.

APPENDIX M

ENGINEERING NOTES

This appendix is a catch-all for design notes, process development, and other items of note that do not fit anywhere else in the document.

IMAGE RESOLUTION TEST PATTERN

This test pattern in Figure M.1 was copied from xxx and printed on a Kodak digital image printer at a Walmart Superstore. Unfortunately the print was too coarse to use to test the resolution of the USB microscope.

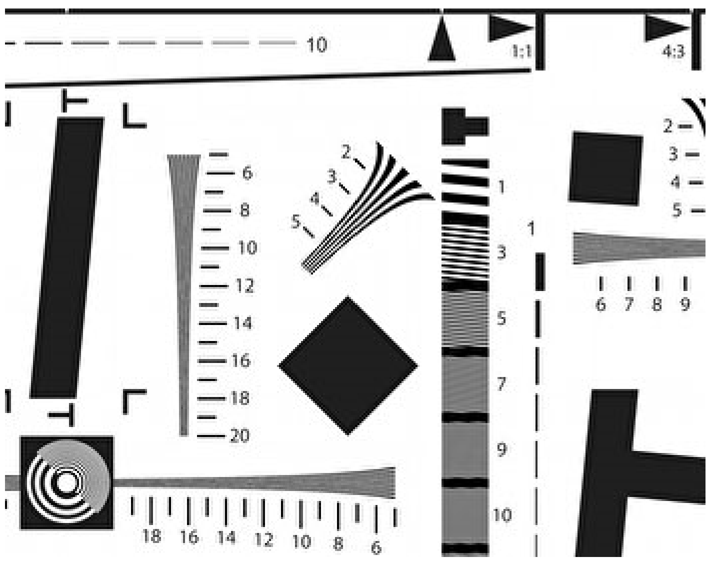


Figure M 1 Resolution Test Pattern

MATLAB EDGE DETECTION SCRIPT

The following is the Matlab script used to process the coins.jpg image.

```
% testedge.m
% This script processes coin.jpg using the
% Canny, Zerocross, and Sobel Edge Detection Algorithms
% and generates images of the results.
%
% Linda Graham
% July 20, 2010

I = imread('coins.jpg');
a2g=rgb2gray(I);
BW1 = edge(a2g,'zerocross');
BW2 = edge(a2g,'canny');
BW3 = edge(a2g,'sobel');
IM1 = imcomplement(BW1);
IM2 = imcomplement(BW2);
IM3 = imcomplement(BW3);
Figure('name','Zerocross Edge Detection Algorithm'), imshow(IM1)
Figure('name','Canny Edge Detection Algorithm'), imshow(IM2)
Figure('name','Sobel Edge Detection Algorithm'), imshow(IM3)
```

Figure M. 2 Matlab Script used for Edge Detection Testing

TESTING DIGITAL CAMERA IR SENSITIVITY

To determine the IR sensitivity of a digital camera requires an IR source. Television remote controls work well for this experiment.

1. First, turn on the camera then turn on the live LCD panel.
2. Then point the television remote control directly at the camera lens and press the ON or POWER button.
3. If the camera does not have a viewing panel, take an image instead.

If the digital camera is IR sensitive, the remote control IR will light up like an LED, or blink on and off. Figure M.2 shows that the USB microscope used in this thesis project is IR sensitive.

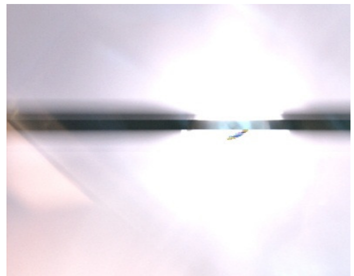


Figure M.2 IR Sensitivity Test for USB Microscope

REVERSE ENGINEERING

Reverse engineering is more than copying a competitor's product. It is also used to re-design damaged or broken parts that are too expensive to purchase or are no longer available. Reverse engineering is also used to design a new part, copy an existing part for which no blueprint is available, and improving inspection techniques.

Ethics. When one hears the phrase 'reverse engineering' what comes to mind? Unethical behavior by industry and academia? The theft of intellectual property? Does the phrase really mean anything today? Reverse engineering has been used to describe any process that involves taking something apart and analyzing how it works. Copycatting restaurant recipes is a form of reverse engineering. The Japanese company, Sankyo, reverse engineered music box movements after WWII. (Music Boxes, 2010)

Many times reverse engineering is used because it is just as fast to use manual inspection methods to redefine a design than it was to generate a new design. In dimensional metrology, new tools such as 2D and 3D scanning techniques make quick work of measuring and reproducing a competitor's product.

The ethical concerns with reverse engineering fall in the realm of infringing on patent or process rights. Learning from others is okay, but blatantly copying their work isn't. Understanding what competitors have accomplished is vital to the success of a business, but reproducing their efforts precisely is dishonest. (Ethics and Reverse Engineering, 2006)

Laws Regarding Reverse Engineering. Reverse engineering is a legitimate form of discovery and has been upheld by both legislation and court opinions. The U.S. Supreme Court has declared that "under the principles that it is an important method of the dissemination of ideas and that it encourages innovation in the marketplace." (Frequently Asked Questions (and Answers) about Reverse Engineering)

Forensic Engineering. In some ways forensic engineering parallels reverse engineering in the both fields use very similar processes to understand how things work – or are supposed to work. Forensic engineering is the process of analyzing product, process, or structural failures for litigation support. After an accident, the forensic engineer: (Forensic Engineering)

1. Examine the broken parts and generates a list of probable causes of failures.
2. Conduct interviews to determine the sequence of events leading up to the failure.
3. Review drawings, specifications, and procedures
4. Use analytical and testing tools to confirm the findings.

DYNAMIC RANGE

Although the meaning of dynamic range for a real-world scene is simply the ratio between lightest and darkest regions (contrast ratio), its definition becomes more complicated when describing measurement devices such as digital cameras and scanners (Cambridge In Colour, 2011).

Most consumer and low-end professional digital cameras have a dynamic range about the same as traditional slide film. Digital cameras can do an adequate job of controlling contrast when lighting conditions are good. If lighting is not typical, for example: extreme high contrast or night-time shooting, digital camera exposures may be disappointing (Aites , 2006).

One way of measuring dynamic range is by bit depth. Bit depth is described as the number of unique colors that are available in an image's color palette in terms of "bits." Digital cameras make it easy to find this number by simply viewing the image file properties. In Figure 2.16, an example of the properties of an image from a USB microscope generated image are displayed.

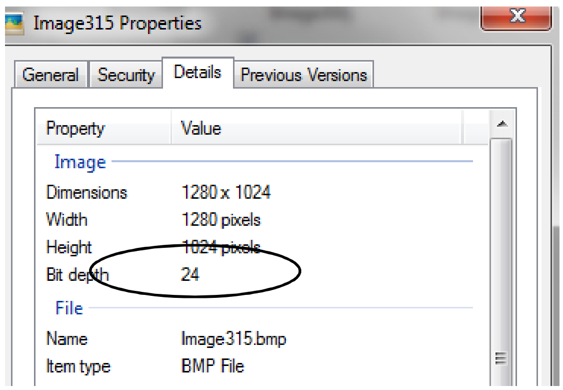


Figure M 3 Digital Image Properties. Microsoft Windows 7 File Properties Menu

Color pixels in a digital image are created from some combination of red, blue, and green. Each color is referred to as a color channel and can have a range of intensity values specified by its bit depth. The bit depth for each primary color is "bits per channel". "Bits per pixel" (bpp) is the sum of all three color channels and represents the total colors available at each pixel. Bit depth represents the number of colors available for each pixel. Most digital cameras have 8 bits per channels 2^8 or 256 color combinations. If all three channels are combined then the image has 2^{3*8} or 16,777,216 different colors or 24 bpp, also called true color (Cambridge In Colour, 2011).

PRIMITIVE PHOTOMICROGRAPHIC METHOD

A simple but primitive method for taking photomicrographic images with film or digital is to simply place the camera lens right on the ocular guard (see Figure M.4). Hold the camera firmly with one hand and use the other hand to focus the image and snap the picture (nickp, 2010).

Figure M 4 Holding a Camera to a Microscope Ocular, Resulting Image at Right

In Figure M.4, the dark circle in the right image is the edge of the eyepiece, not vignetting.

ROUNDNESS

Traditionally roundness is measured by physically contacting the object and taking measurements. The measurements are performed in one of two ways: Diametral or radial. Diametral roundness measurements are performed with measuring instruments that contact the object with two points such as micrometers, calipers and indicators. Diametral roundness measurement is performed at specific points on the round surface. Radial roundness measurements are conducted using precision spindle instruments. Precision spindle instruments are sophisticated, expensive and measuring an object can be time consuming. Coordinate Measuring Machines (CMMs) have started being used for measuring roundness, but process can be slow if a large the number of measurement points are needed. Machine vision methods; however, are very quick and also very useful for measuring very thin round objects that would likely be damaged or destroyed using contact measurement instruments.

Measuring Roundness using a 2DNCMT. Diametral and radial roundness measurements measure cylinders. A 2DNCMT can only measure a round surface. This makes the 2DNCMT an excellent choice for measuring thin round objects.

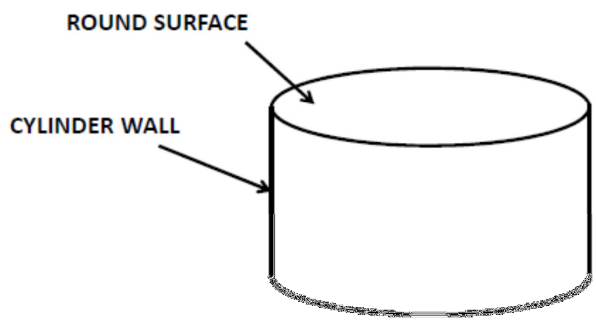


Figure M 5 The 2DNCMT can Measure Round Surfaces
Note: Diametrial and radial roundness measurements measure cylinders.

A few methods have been devised for measuring roundness using noncontact measurement methods. Since the images are digital. It is easy to collect hundreds or thousands of points from the processed image of an object's silhouette.

Now, there is a need to back up a step in the 2DNCMT process. A vector image produced by a 2DNCMT is a vector image and since round shapes are never truly round, they are not translated as perfect circles but as line segments that have a circular shape. One way to tell them apart is CAD generated circles have center marks. Segmented circles do not.

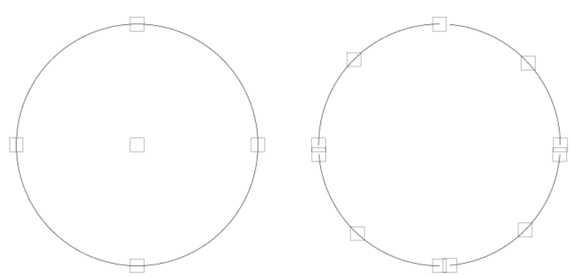


Figure M 6 Circles Generated in 2D CAD
Left: a circle generated in 2D CAD. Right: a vector graphics image with multiple line segments.

There are several methods for verifying roundness of a surface. Software is available to automatically calculate roundness error. For this thesis project, a manual method was selected in order to avoid purchasing software.

Freeware software, DXF2XYZ v2.0, was selected for this project. DXF2XYZ will convert an AutoCad DXF formatted file into a simple text file of xyz coordinate data. The data can be copied into a MS-Excel spreadsheet for further manipulation.

Peak-To-Valley Out of Roundness. In 'A simple Algorithm for Evaluation of Minimum Zone Circularity Error from Coordinate Data' (2002) P.B. Dhanish describes a simple algorithm for determining minimum zone circular error using CMM coordinate data.