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# Size Effects in Human Visual Inspection for Micro/Meso Scale Parts

Sri Harsha Kavuri
*University of Nebraska-Lincoln*, sriharsha2@gmail.com

# SIZE EFFECTS IN HUMAN VISUAL INSPECTION FOR MICRO/MESO SCALE PARTS

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Sri Harsha Kavuri

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# SIZE EFFECTS IN HUMAN VISUAL INSPECTION FOR MICRO/MESO SCALE PARTS

Sri Harsha Kavuri, M.S.

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Advisor: Ram Bishu

Visual inspection has been a major method of quality control in conventional manufacturing processes for the last fifty years. Utilizing trained human inspectors to perform this visual inspection has been the most effective means of maintaining quality control. Extensive research has been performed to understand the factors that influence the human inspection process.

In the recent years, there has been a significant emphasis on manufacturing at the smaller end of the size-spectrum such as Micro and Meso scale manufacturing. Quality control at becomes a challenging task due to the extremely small sizes. Several automated visual inspection techniques have been proposed to increase inspection capability. However, the implementation of these automated techniques requires a large capital investment which makes it unviable for small/medium scale manufacturing companies. Human visual inspection continues to be the major inspection method for these organizations.

Due to the extremely small sizes, some level of magnification is required to facilitate through visual inspection. Visual aids such as microscopes, borescopes are extensively used for this purpose. The level of magnification depends on the size and the detail of the object being inspected. There is no established procedure to choose the level of magnification required for a certain inspection task.

There have been no studies attempted to model the relationship between inspection time and the level of magnification being used. Such a model would help better understand the effective levels of magnification required for a certain inspection task. This study attempts to model the relationship between inspection time and the level of magnification.

A visual inspection experiment was developed with a combination of the major factors that influenced visual inspection accuracy. This was tested on a group of sixty subjects from two distinctive age groups in a PC based environment. The time taken for inspection and the accuracy of responses were recorded in real-time through this experiment.

A MANOVA and ANOVA was performed on the data obtained from the visual inspection experiment. It was observed that magnification was not a significant factor for the data considered for this experiment. This indicates that the above mentioned approach may not be valid to model the relationship between inspection time and magnification.

*Dedicated to my dearest Tatagaru*

*Your life is an inspiration and your memories will be cherished forever*

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# CHAPTER I
# Development of concept

## 1.1 Problem introduction

In the present day world, quality control has become vital in all walks of life. The scope of quality control encompasses a broad range of fields. Quality is a fundamental part of the manufacturing segment. The term ‘Product Quality’ is frequently used to refer to the fabrication of products that meet the basic requirements desired by a customer.

Quality is also an integral part of the service sector. The term ‘Service Quality’ is used to define a service that meets the expectations of an end user. Customer satisfaction is the primary means to measure the quality of service.

Inspection is a very vital part of quality control in the present day macro-manufacturing processes. Industries employ 100% inspection of their products before they are delivered to the end customers. Human visual inspection is one of the most popular methods of visual inspection. It has been the primary method of quality control for last fifty years.

There has been extensive research done to understand the factors that affect human visual inspection performance. Studies performed by Chan ( 2004) concluded that linear magnification had a significant effect on target detection capability. The findings of Gallwey (1986) indicated that an increase in task complexity neagtively affected inspection performance. The same study also indicated that age did not play a significant role in effecting inspection performance with an increase in task complexity.

In the last couple of decades there has been a significant emphasis on Micro/Meso manufacutring processes. The findings of Kornel (2002) suggest that the need for miniaturization and miniature devices has increased drastically in the last decade. Market segments such as optics, biotechnology, medicine and avionics are some of the areas where there is a great demand for these technologies.

The objective of this work is to study the factors that affect visual inspection for Micro/Meso scale parts.

## 1.2 Scope of this research

With the increase in demand for Micro/Meso sized products, the emphasis on quality control for micro parts has gained significant precedence. Visual inspection is one of the primarily used quality control techniques for inspection of these parts. Many industries rely on human inspectors for visual inspection. Due to the extremely small sizes, the use of visual aids to magnify the micro-sized parts becomes a fundamental part of the human visual inspection processes.

The primary focus of this thesis is to study magnification and predict its effect on inspection of Micro/Meso sized parts. This study would help better understand the effectiveness of visual aids in human visual inspection. The development of a model that can quantify the relation between magnification and inspection performance would not only help understand ideal levels on magnification, it would also help industries decide if human inspection is an ideal method of visual inspection.

## 1.3 Thesis outline

The rest of this thesis is presented in four chapters. It begins with Chapter 2 where a summary of published literature is provided on quality control and the quality control techniques employed to maintain quality control. Chapter 3 provides the research rationale, scope of the thesis and research objectives. Chapter 4 presents the research methodology which includes details of the visual inspection experiment developed for the sake of the thesis and how the data was obtained. Chapter 5 gives a description of the study results. Chapter 6 gives a summary of the conclusions observed from this study.

# CHAPTER II
# Background Information

## 2.1 Introduction to quality control

Quality control is a concept that is difficult to define with precision. It can be defined as a set of activities intended to ensure that quality requirements are actually being met. Another more fundamental definition of quality control is making a product that meets the expectations of the customer.

The emphasis on quality control began in the 13$^{th}$ century in Europe when craftsmen formed unions called “guilds” to discuss their craft. A newer model called the “factory system” with more emphasis on the product inspection came into in 1750 and grew during the industrial revolution. In the early 20$^{th}$ century, manufacturers began to include quality processes in quality practices. History of Quality: ASQ (n.d.)

Gilmore (1974) defined quality as conformation to specifications. Juran (1988) defined quality as “fitness for use”. Taguchi (1986) defined it as “loss imparted to the society from the time the product is shipped”. Parasuraman (1985) defined it as “meeting and/or exceeding the customer expectations”. Cooper (2002) defined quality as “the degree to which a process, product or service satisfies a specified set of attributes or requirements”. Feigenbaum (1982) described quality as "the single most important force leading to the economic growth of companies in international markets". American Society for Quality (n.d.) defines quality control as “The observation techniques and activities used to fulfill requirements for quality”

Quality can be broadly classified into two major categories:

1. Product Quality

2. Service Quality

### 2.1.1 Product Quality

The Business Dictionary (n.d.) defines product quality as “The group of features and characteristics of a saleable good which determine its desirability and which can be controlled by a manufacturer to meet certain basic requirements"

The critical parameters that define product quality may vary depending on the type of product. In an automobile manufacturing setting, the performance and safety of a component are important parameters that determine the quality of the product. For a company that makes medical devices, safety for the patients and ease of use for the physicians are the vital parameters. When there is a big deviation between the product specifications and the predetermined standards it can be said that the product is of inferior quality.

Product quality can be measured by the degree of conformance to the predetermined standards and specifications. These measurements can be done by a broad range of inspection methods. As mentioned in the previous section, visual inspection is one of the major inspection methods used to measure product quality.

Therefore, it is critical to ensure that all manufactured parts conform to the specifications set according to the customer requirements. To make sure that the parts are manufactured according to the predetermined specifications, organizations have to make sure that the manufacturing process is under control. This makes process control a very important part of product quality control.

#### *2.1.1.1 Process quality control*

Statistical process control (SPC) is the application of statistical techniques to determine if the outputs of a process conform to the target product or service models. SPC is applied in order to monitor and control a process which ensures that it operates at its full potential. At its full potential, the process can make as much conforming product as possible with a minimum (if not an elimination) of waste. An important module in SPC is using control charts: tools that indicate if an ongoing process is in a state of statistical control.

### 2.1.2 Service Quality

Service quality can be defined as an assessment of how well a delivered service conforms to a client's expectations. Assessment of service quality is important for service business operators as it is important for them to assess the quality of service being provided to their customers and to improve their service, to quickly identify problems, and to better assess client satisfaction.

Freund (1985) stated "the characteristics of a product or service that bear on its ability to satisfy stated or implied needs". Parasuraman et al (1988) did a study in which tried to quantify the major factors which determined service quality. The five major factors they identified were: tangibles, reliability, responsiveness, assurance and empathy. Chakrapani (1998) developed a service quality model consisting of three dimensions: aspects of the product/service, dependability and exceeding expectations.

Service quality can be classified into two categories: Hard and Soft. Hard measures are objective. They can be laptop downtime or fraction of phone calls answered. Soft measures are based on subjective and intangible measures. Customer satisfaction with a particular speed of service is a good example of soft quality measures.

The focus of this study is on product quality and the use of visual inspection as a means to measure the degree of conformance. In the following sections, background researches on the factors that affect visual inspection are discussed in detail.

## 2.2 Factors affecting visual inspection in Product Quality

Defects are a common occurrence when manufacturing of various components is done. Visual inspection is one of the major methods employed to maintain quality control.

Visual inspection can be a process that is either *manual* such as inspection of a product for defects using the human eye, or *automated*, which includes the use of machine vision systems or computer based algorithms to identify the defects in a product. In the following sections, there will be a detailed discussion about factors that affect manual inspection.

### 2.2.1 Effect of age

In a study carried out by Gallwey et al (1986), the visual search performance was tested on an inspection task to understand how increase in complexity impacts the performance. For this study, two distinct subject categories were considered. One set included industry quality control personnel and the second set included students. The test complexity was increased by increasing the number of different fault types. The numbers of fault types used were varied between two, four or six faults to increase complexity. The other means of increasing test complexity was by varying where the faults occurred. Some of the items had faults located only in one sub-area whereas others had faults distributed all through the test. It was concluded from their study that the increase in number of faults had a very significant impact on the performance.

The inspector performance decreased with an increase in the number of fault types. It was also concluded that limiting the faults to one sub-area or spreading them across the entire item did not impact performance. The performance did not vary significantly between the two categories of subjects considered for the experiment.

### 2.2.2 Effect of size

Size is an important factor that has a significant effect on visual inspection performance in manual visual inspection. Increasing/decreasing the size of the object being inspected affects the time taken and the accuracy of inspection. In the case of visual inspection where visual aids are used, magnification is used as one of the major methods to control size. In the following sub-sections, the background literature on effects of magnification in manual visual inspection is discussed.

#### *2.2.2.1 Magnification effect in manufacturing processes*

Nayyar (1963) investigated the effects of magnification on the duration of elements of a subminiature assembly operation. The task consisted of grasping a metal dot with tweezers, transporting it to a hole, and dropping it into the hole. A binocular type industrial microscope was used for performing the task under three levels of magnification. Precision of the task was varied by changing the diameter of the hole into which the dot was assembled.

Results indicated that no single magnification was optimum for all elements. There was no evidence that the optimum magnification is dependent upon the precision requirements of the task.

Wei (1978) examined the effect of lighting and low power magnification on inspection performance. Ten subjects tried to identify c's (defects) in a matrix of 0's (good items) with five letter sizes, three magnification levels (none, 2x and 4x) and three illumination levels (1100, 2200 and 4400 lux). Using time as the criterion, when the target gap was larger than 2.5 min of arc, no magnification was best; below 2.5, 4x was best. Using errors as a criterion, no magnification was best for gaps larger than 2.5 min of arc; below 2.5, 4x was best. Illumination had no effect on errors.

A study performed by Drury (2002) mentions the use of magnifying instruments such as microscopes and borescopes as an integral part of the visual inspection process. This paper mentions the distance between the lens and the surface being inspected as a major factor that affects detection rate. Ideal lens to surface distances reduce field of vision and increase inspection times.

Chan (2004) studied the effect of four levels of linear magnification (no scaling, 1.3 times scaling, 1.69 times scaling and 2.2 times scaling) on detection of peripheral visual targets on four axes. Performance was measured by the linear dimensions of the sensitivity limit on a meridian (in degrees) and by the number of locations at which targets were correctly detected within the sensitivity limits on each axis.

The sensitivity limit was defined as the farthest eccentricity at which 50% correct target detection was achieved. It was concluded from the experiment that detection performance with scaled stimuli was better than performance with non-scaled stimuli which was shown by the increase in sensitivity limits with the increase in scaling. However, enlarging object size at central locations to the same degree as those in the periphery yielded little benefit under the conditions of the experiment.

In another study performed by Chan (2006) two experiments on the detection of peripheral visual targets were conducted. The first experiment was on non-linear and the second experiment on linear magnification. In the first experiment, two levels of non-linear scaling were compared with non-scaling. Performance with scaled stimuli was better than that with non-scaled stimuli, on each of the four axes tested. An unexpected decline in performance was found at the least eccentric target location for the highest level of scaling.

The second experiment investigated the effect of four levels of linear magnification and found that performance with scaled stimuli was better than performance with non-scaled stimuli. However, linear scaling of objects at central locations to the same degree as those in the periphery yielded little benefit here.

Both linear and non-linear magnification facilitated peripheral target detection performance but, perhaps because of the effects of lateral masking, neither linear nor non-linear magnifications seem to compensate completely for performance decrement with eccentricity.

It was suggested that enlarging both the objects and the inter-object spacing in practical industrial inspection situations must involve a trade-off between the number of objects in the viewing area and the scaling level to attain acceptable performance with least magnification.

Lee (2009) investigated the effectiveness of the novel differential linear and differential nonlinear magnification methods, and the effects of magnifier shape and magnification power on visual search performance. With the differential magnification, objects that were more peripheral were scaled at a level higher than those in the vicinity of fixation. It was hypothesized that the differential magnification methods would enhance magnification effectiveness and thereby improves inspection performance. It was also hypothesized that for the same area of magnified view, an elliptical magnifier would be more effective than a circular one. The results showed that 4x magnifications increased the overall inspection time as compared with 3x magnifications, suggesting that a trade-off might have occurred between magnification and field size.

Nakajima (2013) examined the inspection times that affected defect detection in visual inspection utilizing peripheral vision. The fixation duration and the distance between defect and the fixation point are experimental factors in determining the inspection time. It was observed that the main factor that affected the defect detection rate in the visual inspection was the size of the defect. This effect was found to reduce in the order of the distance between the fixation point and the defect, and the fixation duration.

In case of a large sized defect, the detection rate is high regardless of the fixation duration and the distance between the defect and the fixation point. In case of a small sized defect, when the fixation duration is longer and the distance between the defect and the fixation point is closer, the defect detection rate is higher.

*2.2.2.2 Magnification effects in health care*

Sellors et al (2004) evaluated the use of a hand held magnifying device as an alternative to naked eye visual inspection with acetic acid. An analysis was carried out to study the reproducibility and clinical accuracy of the magnification device. Using the findings, the feasibility of increasing the performance and reducing the cost of a hand-held scope was examined. It was found the hand-held scope had a slightly higher sensitivity than naked eye visual inspection with acetic acid (60.7 versus 55.7%, $P < 0.05$) without loss of specificity. The availability of improved materials for optics and illumination suggests that a hand-held scope with enhanced performance is feasible.

Perker et al (2009) evaluated the efficiency of operating microscopes compared with unaided visual examination and intraoral radiography for proximal caries detection. The study was based on 48 extracted human posterior permanent teeth. The teeth were examined with unaided visual examination, operating microscope, and conventional and digital intraoral radiographs. The efficiency of the operating microscope was found to be statistically equal with unaided visual examination, and lower than radiographic systems for proximal caries detection.

Fabbro (2010) compared endodontic therapy performed using magnifying loupes, surgical microscopes and endoscopes. Three prospective studies were included, all dealing with endodontic surgery. From the results of these studies it was observed that there was no significant difference in outcomes found among patients treated using magnifying loupes, surgical microscopes or endoscopes. It was concluded that the type of magnification device can only minimally affect the treatment outcome.

Bernstein (2013) reviewed the quality of cadaveric digital nerve repairs using either loupe or microscopic magnification. Ninety cadaveric digital nerve repairs were performed by nine hand surgeons using loupe or microscopic magnification and evaluated by a visual grading scale. Univariate and multivariate analyses were used to evaluate repairs. Six publications involving 130 repairs with loupes (4–6x) and 255 repairs with microscopes were examined. The surgeon, level of training, repair time, and stitches per repair were not significantly related to an excellent repair.

It was concluded from the study that microscope use produces superior quality digital nerve repair. Approximately half of hand surgeons use loupes in current practice, mostly at low magnification (2.5–3.5x). In this context, a higher level of magnification may be positively correlated with better clinical outcomes.

Kielbassa (2006) evaluated the cavitation rate of proximal caries using different magnification aids in vitro. Radiographs of 285 extracted teeth were taken and the proximal surfaces were graded to the criteria R0 (no radiolucency), R1 (radiolucency confined to the outer half of enamel), R2 (inner half of enamel) and R3 (outer half of dentin). Subsequently, the proximal surfaces were checked for the presence of cavitations with the naked eye (NE), and by using 4.3x magnification eyeglasses (ME), a stereo microscope (SM, 10x), or a scanning electron microscope (SEM, up to 2000x magnification).

It was concluded that a simple visual examination of the surface is not considered appropriate to detect the slightest surface breakdown of caries lesions even under laboratory conditions. Therefore, in particular with lesion sites which are directly accessible, magnification aids should be used in clinical observations for the detection of proximal cavitation.

Studies from the health care industry were reviewed in this section. It can be observed that magnification in general plays a beneficial role in visual inspection for the health care industry.

## 2.3 Types of manufacturing

Manufacturing can be defined as the process of converting raw materials, components or parts into finished goods that meet customer expectations and a required set of specifications.

Emphasis on manufacturing and manufacturing industries started growing in the 18$^{th}$ and 19$^{th}$ centuries with the Industrial Revolution. It began in Britain, replacing labor intensive textile production with mechanization and use of fossil fuels. Manufacturing industries can be classified into broad categories depending on the application. Engineering industries, chemical industries, energy industries, plastics and telecommunication industries are some of the examples of manufacturing industries.

There are several processes used for manufacturing of parts. Casting, molding, forming, machining, joining and rapid machining are some of the conventionally used techniques in manufacturing.

According to a study carried out by Vollertsena et al (2009) on manufacturing of metallic components, the size of the part plays an important role for the process behavior. These size effects lead to changes in process behavior for Micro/Meso scale manufacturing.

Manufacturing processes can be classified into three major distinct categories based on the size.

1. Macro manufacturing

2. Micro manufacturing

3. Meso manufacturing

### 2.3.1 Macro manufacturing

Traditional manufacturing processes such as casting, molding, machining fall under this category. Macro manufacturing involves the manufacturing of components that are visible to the naked eye and that can be touched or handled by humans without the necessity of any magnification instruments. Examples of products made using macro manufacturing include various things that we use in our day to day life.

### 2.3.2 Micro manufacturing

According to Francesco et al (2011), micro manufacturing can be defined as the process of fabricating miniature structures in the order of micrometers and smaller. The manufacture of these miniature parts and devices has been a growing field in the recent past. The increased demand for these parts primarily in the biomedical, microelectronics and telecommunications sector has brought in a huge influx of micro sized parts into the industry.

For conventional usage, most of the parts that cannot be produced by conventional means such as milling, drilling, turning, and grinding are in the Micro/Meso size area. As the size of the manufactured parts further decreases, conventional manufacturing techniques become obsolete for use and more specialized manufacturing techniques are needed.

### 2.3.3 Meso manufacturing

Meso in physics means a scale between the micro and nano levels. The sizes manufactured under meso may range between 100 nanometers to 1000 nanometers. Hence meso manufacturing is an extension of micro manufacturing at smaller sizes.

According to a study carried out by Vittorio (2001) the development of Microelectromechanical systems (MEMS) has played a major role in the increase of the number of parts that are being manufactured on the Micro/Meso scale. Microelectromechanical systems (MEMS) are small integrated devices or systems that combine electrical and mechanical components. They range in size from the sub micrometer (or sub-micron) level to the millimeter level. MEMS extend the fabrication techniques developed for the integrated circuit industry to add mechanical elements such as beams, gears, diaphragms, and springs to devices.

The development of machines with suitable motion control and accuracy for the micro manufacturing processes and lack of efficient process control measures are some of the challenges that are being faced in the development of Micro/Meso scale products. From a quality control point of view, the inspection techniques used for meso scale parts fall under the same spectrum as the micro inspected parts. Hence they are not discussed separately for this study.

## 2.4 Effect of process control in macro manufacturing

As mentioned earlier, visual inspection is one of the major quality control techniques used in process control for manufacturing processes. Visual inspection can be classified into manual visual inspection and automated visual inspection. The background research on the various factors that affect manual visual inspection were discussed.

In this section, the various manual and automated visual inspection techniques are discussed.

### 2.4.1 Manual visual inspection

Manual visual Inspection, used in maintenance can be defined as inspection of equipment and structures using either or all of the human senses such as vision, hearing, touch and smell and/or any non-specialized inspection equipment. It can also be defined as a routine stage of a finishing operation that involves closely examining a part with the naked eye immediately following its production to check for defects.

In a paper published by Drury (2002), manual visual inspection was defined as the process of using the unaided eye, alone or in conjunction with visual aids, as the sensing mechanism from which judgments were made about a unit being inspected. It is the primary inspection method used in aircraft maintenance. These tests generally cover a broad area of the aircraft structure. More detailed (small area) tests were conducted using optically aided visual methods. Such tests included the use of magnifiers and borescopes.

### 2.4.2 Automated inspection techniques

It has been established that visual inspection is an important quality control technique used by several industries to accept or reject manufactured product. In the previous sections, manual visual inspection was discussed as a quality control technique. The various factors that affect inspection performance were discussed along with some studies that were aimed at improving the performance of the human inspectors. Automated visual inspection systems have been explored as alternatives to human visual inspection.

Automated visual inspection refers to the use of computers and other auxiliary equipment to accomplish what was previously done using human visual inspection. These techniques are based on the perceived two-dimensional images of real time three-dimensional images.

The components of a conventional automated visual inspection system include a light source, optical systems, a CCD camera, an image acquisition device, and an image processing system. Image processing, precision measurement, pattern recognition and artificial intelligence are some of the major techniques used for automated visual inspection.

These techniques have found extensive applications in the electronics industry particularly in the inspection of printed circuit boards and integrated circuit chips. Some specialized techniques have also found applications in industries such as automobile, packaging and textile industries.

A reseach paper published by Resendiz (2013) describes a computer vision system for automated visual inspection of railroad tracks. This eliminates the laborious and time consuming process of a human inspector inspecting thousands of miles of railroad track twice a week.

The system consists of a track cart with a mini computer system, a power source mounted on the top, and a camera mounted over the side of the truck cart which fetches images of the lateral view and the over-the-rail views of the track. Using an algorithm that utilizes the periodic manner in which the track components repeat, an inspection video is developed. A test run of this automated system showed that it was 87% accurate in identifying the defects in the track components.

## 2.5 Effects of process control in micro manufacturing

Micro manufacturing processes require special technology and most of the conventionally used macro manufacturing techniques are usually not very compatible with the micro manufacturing methods. With the drastic reduction in part sizes, part handling and monitoring takes on a new significance as well. Most of the conventional measurement systems used for inspection of macro parts no longer work.

As it is a major part of all kinds of manufacturing processes, quality control is an important aspect of micro-manufacturing. There have been various quality control techniques that are being used to make sure that the manufactured parts meet the required quality standards. As discussed in the case of macro manufacturing techniques, visual inspection is an important quality control technique used in the manufacture of micro parts.

Visual inspection in micro manufacturing is done to assess quality in several ways: to inspect the surface quality of the manufactured components, to check for alignment and other dimensionally incorrect features, and to make sure any labels or warning signs are placed according to specifications. This visual inspection can be done either manually or by using automated inspection techniques. In the following sub-sections, the automated and manual visual inspection techniques used in micro manufacturing will be discussed in detail.

### 2.5.1 Automated inspection techniques

Various automated computer based vision systems have been proposed to do inspection of these parts.

Sun et al (1992) describe image subtraction as one of the earliest methods to conduct automated inspection of micro components, especially in Printed Circuit Boards (PCB) inspection. It is simple and straight-forward to understand. The board to be inspected is scanned and is compared against the image of an ideal part. The subtracted image can be displayed and analyzed for defects.

Scholz-Reiter et al (2010) proposed an automated visual inspection system for use in inspection of micro-manufactured components. This technique uses confocal laser scanning microscopy to obtain high-resolution 3D images of the object being inspected. These images are processed by an algorithm which is programmed to extract surface defect information. The surface defects are classified using decision trees. There was no information on how this method works in a practical inspection situation.

Duan et al (2008) proposed an Automatic Optical Inspection (AOI) system for the inspection of micro-drill bits used in the manufacture of printed circuit boards. It uses an image registration technique to align the drill bit blade image automatically, which ensures the quality of the printed circuit board.

Garcia et al (2006) proposed a methodology for automated visual inspection of micro-manufactured parts, where the features to be inspected are selected automatically using an automated visual inspection system. A multivariate stepwise discriminant analysis was used in order to automate the feature selection process.

This type of system allows for the automation of the time-consuming task of exploring and selecting features for which algorithms need to be developed for automated visual inspection systems. This feature would be helpful in adapting pre-existing systems for inspection of new components. There was no information presented about testing this system in a practical visual inspection situation.

### 2.5.2 Manual inspection techniques

Manual visual inspection is an integral part of inspection of micro-level parts. These techniques mostly involve the use of visual aids such as magnifying glasses and borescopes. Drury (2002) mentioned the use of microscopes for the inspection of small parts and equipment during aircraft inspection during maintainence.

A study performed by Melchore (2011) indicated that manual visual inspection is an integral part of pharmaceutical manufacutring. Human inspectors are used extensively to inspect for proper form and detection in syringes. Magnification is used to aid the inspection process. It is also used in the inspection of pharmaceutical labels on bottles to detect mislableling, blemishes and proper closure.

Human visual inspection is also a major part of inspection in Printed Circuit Boards (PCB). Although there are several automated inspection techniques currently avaliable on the market for PCB inspection, many small industries continue to use manual visual inspection. A white paper study conducted by JH Technologies (2010) discussed the major factors that are inspected are as follows:

1. Presence and absence of components: To verify the presence of the actual components and ensure that the right components are being used
2. Solder joint quality: The major factors of consideration are to verify if there is enough solder and to verify if the solder joint is good enough for proper functionality

Magnification is an important component of such manual inspection. Magnifications typically used for this kind of inspection vary from 2x to 4x. Various microscopes are used for the inspection depending on size of work area and the actual size of the PCB being inspected.

## 2.6 Summary of literature

This chapter began with an introduction to the concept of quality control. A brief history was followed by definitions of quality control from various research papers and organizations. The major categories of quality control were defined and discussed in detail.

Following the discussion on quality control, visual inspection was discussed as one of the major methods of quality control. The back ground literatures on the various factors that affect visual inspection were discussed. Following this, the different types of manufacturing based on size of the object were discussed. Next, the process control for these various manufacturing techniques using visual inspection was discussed.

# CHAPTER III
# Research Rationale

## 3.1 Concept

Human visual inspection has been a popular method of quality control for the last fifty years. There has been extensive research performed on the factors that impact performance of a human inspector during an inspection task. Published literature over the last few decades has identified several factors that have a significant impact on human visual inspection for conventional macro-manufactured products. Effects of factors such as task complexity, size and age have been studied in great detail.

Increased emphasis on Micro/Meso scale manufacturing has significantly shifted the focus of research to understanding the factors that affect inspection at these extremely small sizes. A number of automated inspection techniques have been developed for inspection of these Micro/Meso scale parts. Some of these techniques have been discussed in the previous chapter.

Although there has been considerable research done in the area of automated visual inspection methods for micro-sized parts, there are severe limitations for their use in small and medium scale companies due to high set up costs and inflexibility for use as suggested in a study by Kommidi (2005).

A study conducted by Melchore (2011) indicated that manual inspection is essential when the use of a fully automated system is not feasible. Manual visual inspection is implemented as the alternative visual inspection technique when using an automated system is not feasible. Available literature has a noticeable lack of information on manual visual inspection for the inspection of micro-manufactured parts. There is a need to develop models that predict the influence of factors that affect manual visual inspection in Micro/Meso scale manufacturing.

### 3.1.1 Effect of magnification in visual inspection

Literature on the effect of magnification in macro manufacturing processes and the medical industry was reviewed in the previous chapter. An overall review indicated that increasing magnification in general played a beneficial role in increasing the performance of the human visual inspector. Studies indicated that some levels of magnification to be beneficial and others ineffective. It was observed that the effect of magnification was significantly affected by the type of task being evaluated.

The optimum level of magnification required for a task varies depending on the object that needs to be inspected. There are no established standards that help organizations understand the optimum levels of magnification required for different sizes of the objects. The literature review indicates that using a low level magnification yielded the same results as using a higher level of magnification.

Magnification is an important factor in several studies associated with micro-manufactured parts. The use of visual aids becomes a vital part of the manual visual inspection processes used for Micro/Meso scale parts. These visual aids enhance the size of the part to a size which would facilitate effective visual inspection by the human inspector.

Microscopes, borescopes and various other hand-held devices have been designed for these inspection purposes. Understanding the correct levels of magnification for these objects is an important factor to be considered when using these magnification instruments. If the magnification levels are too high, it might result in a very large surface area which might take a longer time to inspect and increase the chance of an inspector missing a defect. If the magnification levels are too low, it might cause a defect to escape the inspectors' attention.

### 3.1.2 Development of model

Manufacturing can be classified into three distinct levels based on the size of the object being manufactured. Macro manufacturing in the highest level of size followed by the lower micro and meso levels of manufacturing. Process control is an important aspect of the manufacturing processes to enable mass production of consistent products from continuously operated processes.

Visual inspection is one of the major techniques used to maintain process control in manufacturing. Process control through visual inspection varies from one manufacturing process to the other. For example, in case of macro manufacturing, the use of visual aids for inspection is optional whereas in case of Micro/Meso scale manufacturing it is almost impossible to perform inspection without the use of a visual aid to enhance the size of the object.

It has already been mentioned that there has been a significant increase in focus on the Micro/Meso scale manufacturing processes. Manual visual inspection is one of the major methods of inspection for these Micro/Meso scale parts.

The size of the object being inspected becomes an important factor in the case of manual visual inspection. Increasing/decreasing the size of the object is a vital part of understanding the effectiveness and accuracy of visual inspection processes. A review of literature indicated that the size effect in manual visual inspection for Micro/Meso scale parts has not been studied in great detail.

Magnification is one of the major means to increase/decrease the size of the objects to facilitate manual visual inspection for Micro/Meso scale parts. From the previous sub section it was observed that magnification plays an overall beneficial role in improving the performance of the human inspector during manual visual inspection. It can also be stated that a lack of magnification decreases the performance of the human inspector.

Time taken for inspection is another vital parameter during visual inspection in an industrial setting. The time taken by a visual inspector for inspection is influenced by several factors such as magnification of the object being inspected and the age of the inspector performing the inspection task. High production volumes and low cycle times require the inspectors to be fast and accurate with their inspection processes. Studying the correlation between the various factors that affect inspection times of the visual inspector would be vital for an organization to understand inspection costs and accuracy of their inspectors.

Understanding the correlation between magnification levels and inspection times is important to determine which levels of magnification facilitate faster inspection times. It also helps understand if decreasing magnification increases the search time of the human inspector. Such a correlation becomes vital for industries that employ 100% human visual inspection of their manufactured Micro/Meso scale products.

This study is an attempt to understand how changing levels of magnification have a significant impact on inspection times. It can be postulated that a linear model of search time versus size effect could be used to predict inspection performance in Micro/Meso scale manufacturing.

### 3.1.3 Objectives

Based on the needs identified during the literature review, a comprehensive visual inspection was designed with the aim of addressing the following objectives:

1. Develop a linear model for search time and size effect to predict inspection performance in Micro/Meso manufacturing
2. Evaluate the main factor effects and interaction effects of task complexity, magnification and age on manual visual inspection accuracy

## 3.2 Research methodology

In order to develop a correlation between magnification and inspection time, data from human visual inspectors during a real-life inspection task would be required. Since such data is hard to obtain from organizations due to various reasons, a real life inspection task was simulated on a PC-based environment. A visual inspection experiment was developed with a series of images at varying levels of magnification.

These images would be similar to the images a human inspector would encounter during a routine visual inspection task. Varying levels of task complexity were incorporated into these images to make the experiment more realistic.

To understand how the various levels of magnification impacted performance, some images were classified as defective and some were classified as non-defective. The accuracy and time taken for inspecting the defects were recorded. To make the experiment more realistic, other major factors which influence human visual inspection in the review of literature such as task complexity and age were also considered.

The task complexity for this experiment was varied by changing the density of the images created for the experiment and by using two different types of defects.

Density can be defined as the number of characters within a square unit of area. If there are more characters in a square unit of area the image can be classified as a high density sample. An image which has fewer characters in a square unit of area can be classified as a low density sample. It can be observed that density is similar in concept to magnification.

# CHAPTER IV
# Research method

As mentioned in the previous section, the method for this study was developed in order to analyze the effect of magnification on inspection time and accuracy for inspection of micro-manufactured parts.

A visual inspection experiment was developed with visual material that presented a combination of all the factors except age. The task complexity for this experiment was varied by changing types of defect, density and creating various location of defect for each type of defect. In the following sub-sections, the various steps involved in the development of the method are described in detail.

## 4.1 Creating the visual stimulus

The first step in developing the method was to create visual stimulus or samples that presented a combination of all the four attributes described above.

### 4.1.1 Using 'type of defect' as a factor

The first factor that was considered was the 'Type of defect'. Based on previous studies done with human visual inspection, two types of defects were selected. All the other factors were incorporated into the visual stimulus that was created for the type of defect.

The first type of defect was a character ‘*’ which is unique among an array of repeating special characters (@, #, $,), (, ^). A sample defective image is shown below with the unique defective special character circled in red.

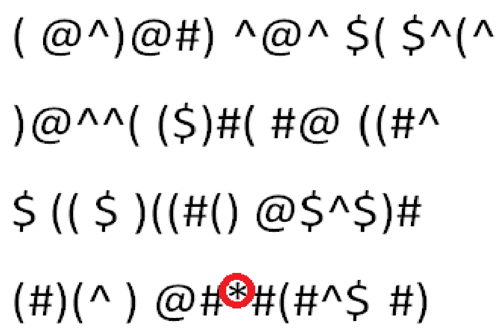



**Figure 4.1 Character sample with defect circled in red**

The second type of defect selected was an object seen in routine visual inspection processes. This was termed as a ‘real sample’ and the design of a Printed Circuit Board (PCB) was used as a ‘real sample’ for this purpose. A uniquely placed triangle in the diagram of a printed circuit board was identified as a ‘defective’ sample. An image of a printed circuit board with the defect circled in red is shown below.

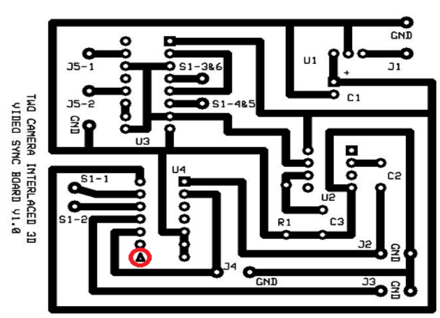



**Figure 4.2 Real sample with defect circled in red**

### 4.1.2 Using location of defect as a factor

As a next step, defects in four unique locations were created for each of the type of defects (character defect and real defect) identified in the previous sub-section. The creation of these unique locations of defects prevents the human subjects from memorizing the location of the defects during the visual inspection experiment.

For the sake of this experiment, the location of defects was assigned numbers from one through eight for identification. Location of defects one through four were identified as 'character defects' and location of defects four through eight were identified as 'real defects.'

### 4.1.3 Using magnification as a factor

Four levels of magnification were created for each of the location of defects. The magnification levels used were scaled up by 100 percent, 75 percent, 50 percent and 35 percent of original size. Using four levels of magnification is expected to present us with enough variability in the results to understand the effect of magnification for manual inspection of micro-manufactured parts.

For the sake of this experiment, the levels of magnification were assigned numbers from one through four for identification. 100% magnification was labeled as one, 75% magnification was labeled as two, 50% magnification was labeled as three and 35% magnification was labeled as four.

### 4.1.4 Using density as a factor

For the final step, two levels of density were created for each of the levels of magnification. The density levels used were high density and low density. The use of these two levels of density will be helpful in evaluating which levels will be the least time consuming and most efficient.

For the sake of this experiment, the levels of density were assigned numbers one and two for identification. High density was numbered as one and low density was numbered as two.

Hence, the 64 samples considered in this experiment can be explained as follows:

Two levels of defects x four levels of location of defects x four levels of magnification x two levels of density = 64 unique visual samples

A total of 60 subjects were selected to participate for these experiments. Subjects were classified as either young (20-30 years) or old (30-60). The gender and ethnicity of the subjects varied from subject to subject and were not considered for the purpose of this study.

## 4.2 Creating a computer based interface to carry out the visual inspection experiment

The next step was to create a computer based interface to enable the visual inspection of the samples created above. A web browser based computer interface was created. A data base linked to this web browser interface contained all the 64 visual samples that were created for the purpose of this experiment.

The first screen that appears on the interface has prompts for the subjects to enter their first name, last name, age, radio buttons to indicate their gender and a check box that states that they have read and understood the instructions of the test on the left side of the screen. The right side of the screen contains instructions for taking the test. Shown below is an image of this interface.

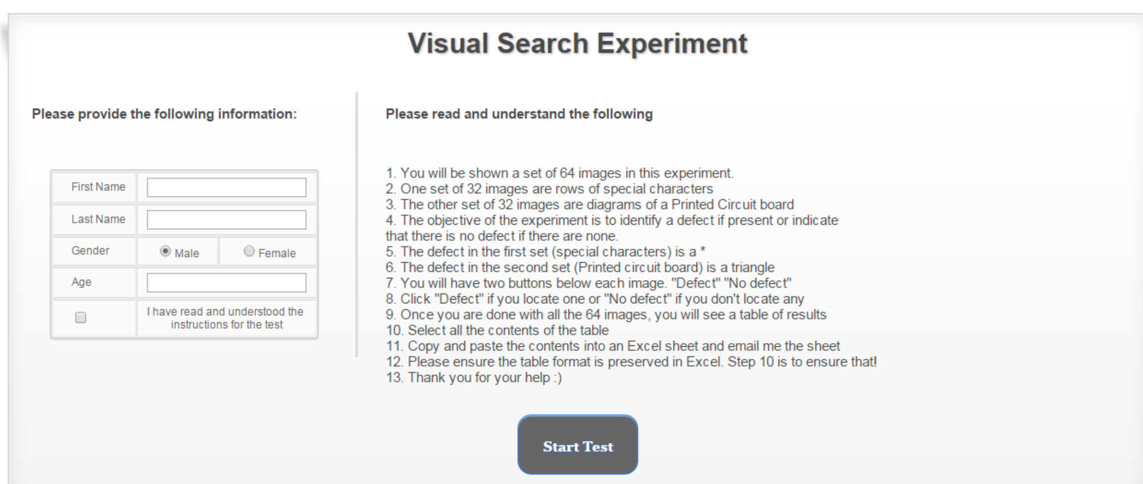



**Figure 4.3 Screenshot of the browser based computer interface used for the study**

Once the subjects have filled in all the required information, the visual samples created appear in a randomized order. There are two buttons on the bottom of the image which read 'Defect' and 'No defect'. Once the subject has finished inspecting the sample, he can indicate if it is a defective sample or a non-defective sample. The computer interface has a clock running in the background which records the time taken by the subject to record a response. A screenshot of the experiment in progress is shown below.

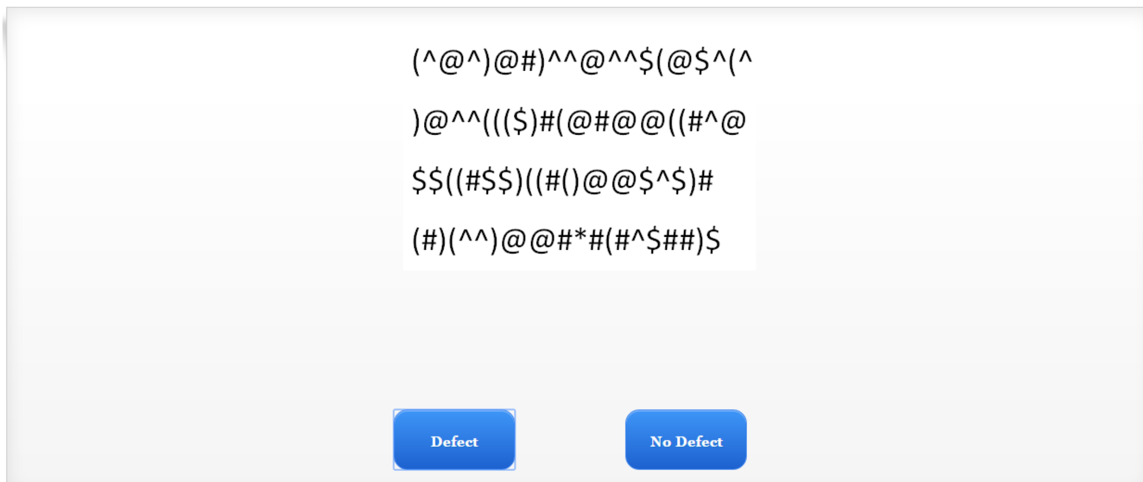
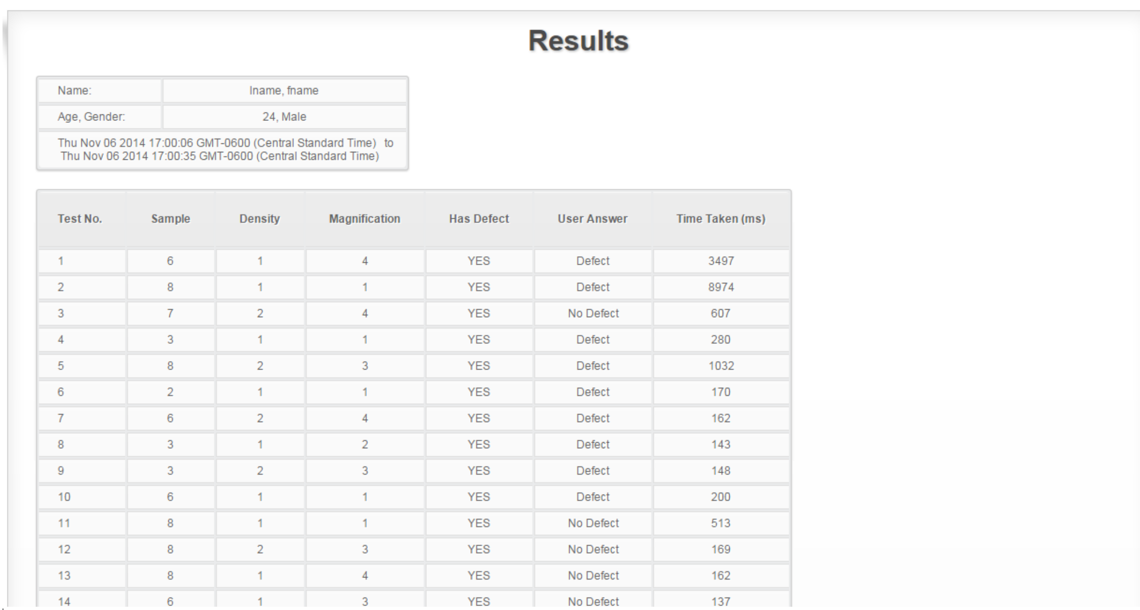



**Figure 4.4 Screenshot of the visual inspection experiment in progress**

After the subjects have finished visual inspection of all the 64 visual samples presented to them, a summary of the results appears in two different tables. The table on the top left corner of the screen contains the name, age, gender, the start time and end time of the experiment.

The second table contains a comprehensive summary of the test number in the order it was presented to the subject, the sample number/location of defect number, the density number, the magnification number, the correct answer to the question, the answer given by the subject and the time taken by the subject to inspect that particular sample.  A screenshot of the results for a test run of the experiment is shown below.



**Results**

| | |
|---|---|
| Name: | lname, fname |
| Age, Gender: | 24, Male |
| Thu Nov 06 2014 17:00:06 GMT-0600 (Central Standard Time) to Thu Nov 06 2014 17:00:35 GMT-0600 (Central Standard Time) | |

| Test No. | Sample | Density | Magnification | Has Defect | User Answer | Time Taken (ms) |
|---|---|---|---|---|---|---|
| 1 | 6 | 1 | 4 | YES | Defect | 3497 |
| 2 | 8 | 1 | 1 | YES | Defect | 8974 |
| 3 | 7 | 2 | 4 | YES | No Defect | 607 |
| 4 | 3 | 1 | 1 | YES | Defect | 280 |
| 5 | 8 | 2 | 3 | YES | Defect | 1032 |
| 6 | 2 | 1 | 1 | YES | Defect | 170 |
| 7 | 6 | 2 | 4 | YES | Defect | 162 |
| 8 | 3 | 1 | 2 | YES | Defect | 143 |
| 9 | 3 | 2 | 3 | YES | Defect | 148 |
| 10 | 6 | 1 | 1 | YES | Defect | 200 |
| 11 | 8 | 1 | 1 | YES | No Defect | 513 |
| 12 | 8 | 2 | 3 | YES | No Defect | 169 |
| 13 | 8 | 1 | 4 | YES | No Defect | 162 |
| 14 | 6 | 1 | 3 | YES | No Defect | 137 |

**Figure 4.5 Screenshot of the results screen**

## 4.3 Compiling the data and importing it into the statistical analysis software

The data obtained from the results summary for each subject is copied into an Excel document. The individual spreadsheets are combined and imported to statistical analysis software. Minitab was used to perform the statistical analysis for this study.

A MANOVA and a two-way ANOVA was performed on this data to understand the effects of the main factors such as type of defects, location of defects, magnification, density and age. The two-way interaction effects between these factors were also studied. A regression analysis was performed to determine how the magnification of a location of defect effects the inspection time when the locations of defects are reduced to micro-dimensions.

The following chapters will have a detailed summary of the results from the MANOVA, ANOVA and regression analysis mentioned above.

# CHAPTER V
# Results

This chapter presents a summary of the results obtained from the Multivariate Analysis of Variance (MANOVA) and the Univariate Analysis of Variance (ANOVA).

The results from the multivariate analysis of variance for the various multivariate tests along with a MANOVA summary for time and accuracy are presented below.

**Table 5.1 MANOVA summary for multivariate tests**

| Description | p-value for Wilks-Lambda | p-value for Lawley-Hotelling | p-value for Pillai's | p-value for Roy’s |
|---|---|---|---|---|
| Location of defect | 0.019 | 0.019 | 0.019 | -- |
| Type of defect | 0 | 0 | 0 | -- |
| Density | 0.547 | 0.547 | 0.547 | -- |
| Magnification | 0.001 | 0.001 | 0.001 | -- |
| Age | 0 | 0 | 0 | -- |

**Table 5.2 MANOVA summary for time**

| | p-Value | Significance |
|---|---|---|
| Location of defects | 0.051 | NS |
| **Type of defect** | **0** | **S** |
| Density | 0.535 | NS |
| Magnification | 0.060 | NS |
| **Age** | **0** | **S** |

**S –** Significant at $\alpha \leq 0.05$ NS – Not significant

**Table 5.3 Accuracy scoring system**

| User answer | Correct answer | Accuracy |
|---|---|---|
| Defect | Defect | 1 |
| No defect | No defect | 1 |
| No Defect | Defect | 0 |
| Defect | No Defect | 0 |

The accuracy was calculated as ‘1’if the subject was able to indicate a defect if a defect was present or indicate that there was no defect if there was no defect in the sample. It was calculated as ‘0’ if the subject indicated that there was ‘no defect’ in case of a ‘defect’ or indicated that there was a ‘defect’ when there is ‘no defect’. The independent factors in this analysis were location of defects, type of defect, magnification, age and density.

**Table 5.4 MANOVA summary for accuracy**

| | p-Value | Significance |
|---|---|---|
| Location of defects | 0.053 | NS |
| Type of defect | 0.131 | NS |
| Density | 0.381 | NS |
| **Magnification** | **0.001** | **S** |
| **Age** | **0** | **S** |

**S –** Significant at $\alpha \leq 0.05$ NS – Not significant

The Univariate analysis of variance was performed for inspection time and accuracy.

The ANOVA summary for time is shown below:

**Table 5.5 ANOVA summary for time**

| | p-Value | Significance |
|---|---|---|
| Location of defects | 0.057 | NS |
| **Type of defect** | **0** | **S** |
| Density | 0.542 | NS |
| Magnification | 0.067 | NS |
| **Age** | **0** | **S** |
| Location of defects x type of defect | 0.059 | NS |
| **Location of defects x density** | **0** | **S** |
| **Location of defects x magnification** | **0** | **S** |
| Location of defects x Age | 0.196 | NS |
| Type of defect x Density | 0.185 | NS |
| Type of defect x Magnification | 0.639 | NS |
| Type of defect x age | 0.303 | NS |
| **Density x magnification** | **0** | **S** |
| Density x age | 0.737 | NS |
| Magnification x age | 0.829 | NS |

**S –** Significant at $\alpha \leq 0.05$ NS – Not significant

The ANOVA summary for accuracy is show below:

**Table 5.6 ANOVA summary for accuracy**

| | p-Value | Significance |
|---|---|---|
| Location of defects | 0.053 | NS |
| Type of defect | 0.130 | NS |
| Density | 0.381 | NS |
| **Magnification** | **0.001** | **S** |
| **Age** | **0** | **S** |
| **Location of defects x type of defect** | **0.014** | **S** |
| Condition x density | 0.502 | NS |
| Location of defects x magnification | 0.840 | NS |
| Location of defects x age | 0.605 | NS |
| Type of defect x density | 0.690 | NS |
| **Type of defect x magnification** | **0.009** | **S** |
| Type of defect x age | 0.094 | NS |
| Density x magnification | 0.989 | NS |
| Density x age | 0.473 | NS |
| Magnification x age | 0.352 | NS |

**S –** Significant at $\alpha \leq 0.05$ NS – Not significant

## 5.1 Main effect plots for inspection time

This sub-section describes the main effect plots for inspection time. The main effects described here are location of defects, type of defect, magnification, age and density. Based on the results from the ANOVA summary table, only the significant main and interaction effects are described in the following sections.

### 5.1.1 Effect of type of defect

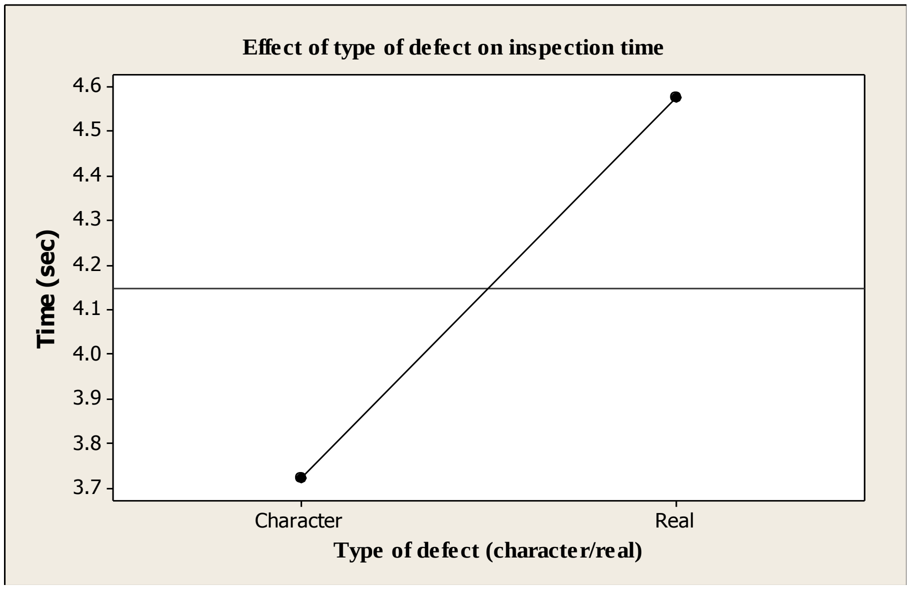



**Figure 5.1 Time versus type of defect**

It can be observed from the above plot that the time taken by a human inspector to identify a Real defect is greater than the time taken to identify a character defect. This difference is very significant in case of this experiment.

It can be inferred from these trends that the inspection of the real sample is more complex when compared to inspecting lines of characters for a specific defect. This can be attributed to the processing power of the human brain. It is easier for the human mind to process characters in comparison to more complex shapes.

### 5.1.2 Effect of age

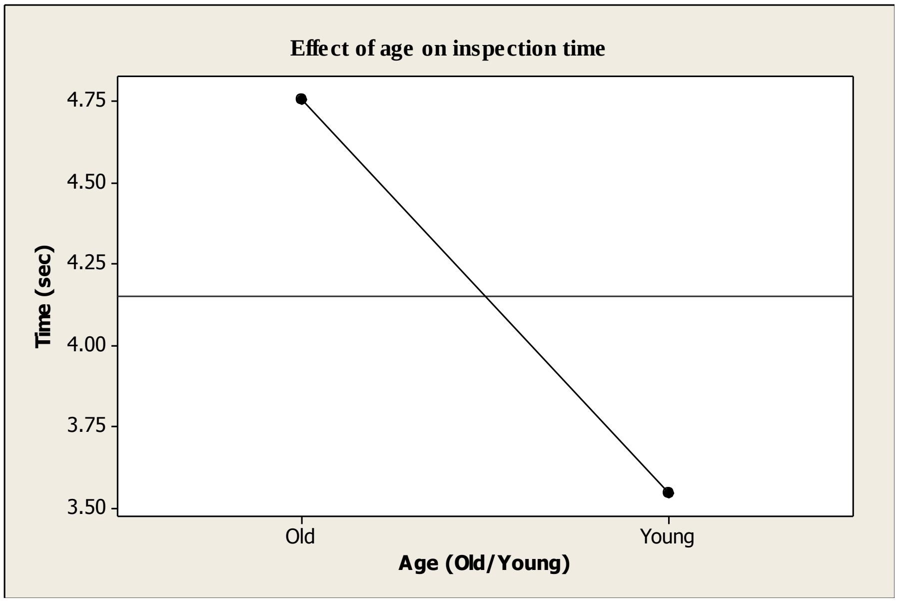



**Figure 5.2 Time versus Age**

It can be inferred from the above plot that there is a significant difference in the average inspection time for the younger and the older subjects. For the purposes of this experiment, young subjects belong to the 20 to 30 years age group and the older subjects belong to the 30 and beyond age group.

This difference in average inspection time between the older and the younger subjects might be attributed to the fact that the younger subjects have better visual acumen and reflexes when compared to the older subjects.

## 5.2 Two-way Interaction effects for time

The following section describes in detail the various two way interaction effects caused by the five main factors are discussed in detail.

### 5.2.1 Interaction effect between magnification and density

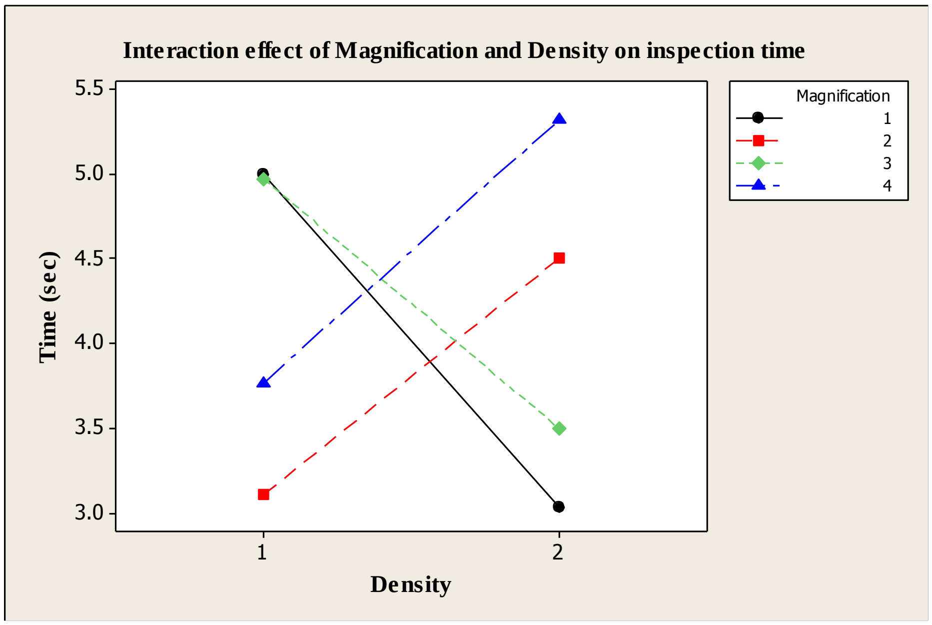



**Figure 5.3 Two – way interaction effects between magnification and density**

It can be observed from the above plot that for magnification one (100% magnification) the time taken for inspection of density one (high density) was more than the time taken for inspection of density two (low density). These observations can be confirmed by performing a Tukey test.

In case of magnification two (75% magnification) the time taken for inspection of density two (low density) was more than the time taken for inspection of density one (high density).

For magnification three (50% magnification) the trend was similar to the trend observed for magnification one. For magnification four the trend was similar to the trend observed for magnification two.

Intuitively, it can be assumed that inspection of lower densities would be less time consuming as compared to higher densities. The trends observed for magnification two and magnification four deviate from these assumptions. This might be attributed to the underlying effects of density and type of defect.

## 5.3 Main effect plots for accuracy

This sub-section describes the main effect plots for accuracy of inspection. The main effects described here are Location of defects, Type of defect, Magnification, Age and Density. Based on the results from the ANOVA summary table, only the significant main and interaction effects are described in the following sections.

### 5.3.1 Effect of magnification

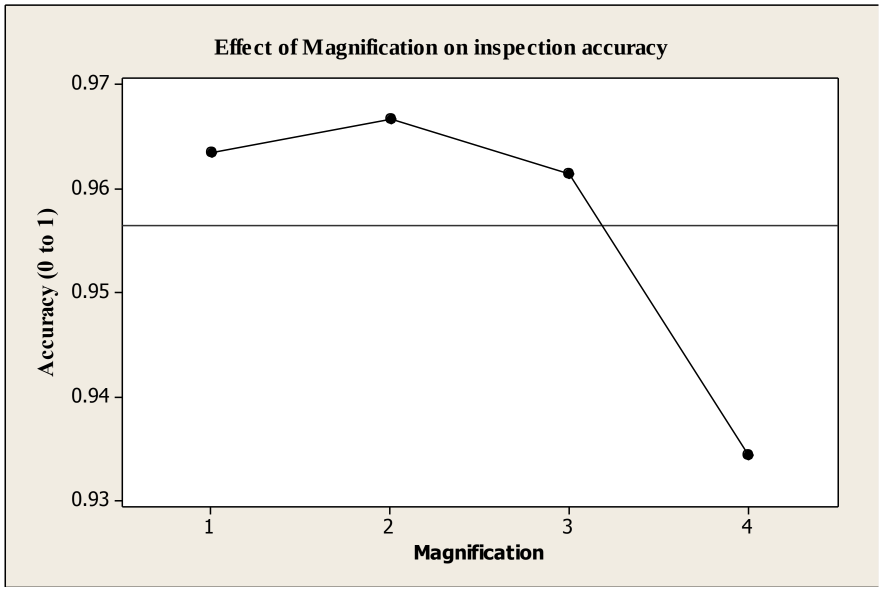



**Figure 5.4 Magnification versus accuracy plot**

It can be observed from the above plot that the accuracy for magnification two (75% magnification) is slightly higher than magnification one (100% magnification) the accuracy for magnification three (50% magnification) and magnification four (35% magnification) is lesser than the respective previous magnifications. For the sake of this study, it can be inferred from the above observations that the 75% magnification is the most ideal size for visual inspection. A Post-hoc comparison between the different levels of magnification was performed using Tukey test. The results indicated that all four levels of magnification are significantly different from one another.

### 5.3.2 Effect of Age

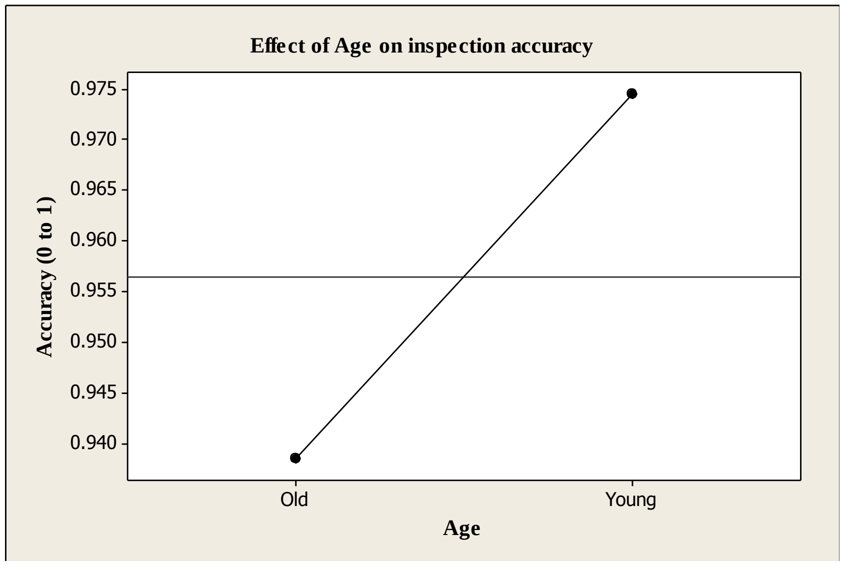



**Figure 5.5 Age versus accuracy plot**

It can be observed from the above plot that the younger subjects had higher visual inspection accuracy in comparison to the older subjects. The younger subjects have quicker reflexes, better eye sight and are motivated to perform in comparison to the older subjects who are slightly slower and have poorer eye sight.

## 5.4 Two-way Interaction effects for accuracy

The following section describes in detail the various two way interaction effects caused by the five main factors are discussed in detail.

### 5.4.1 Interaction effect between Type of defect and Magnification

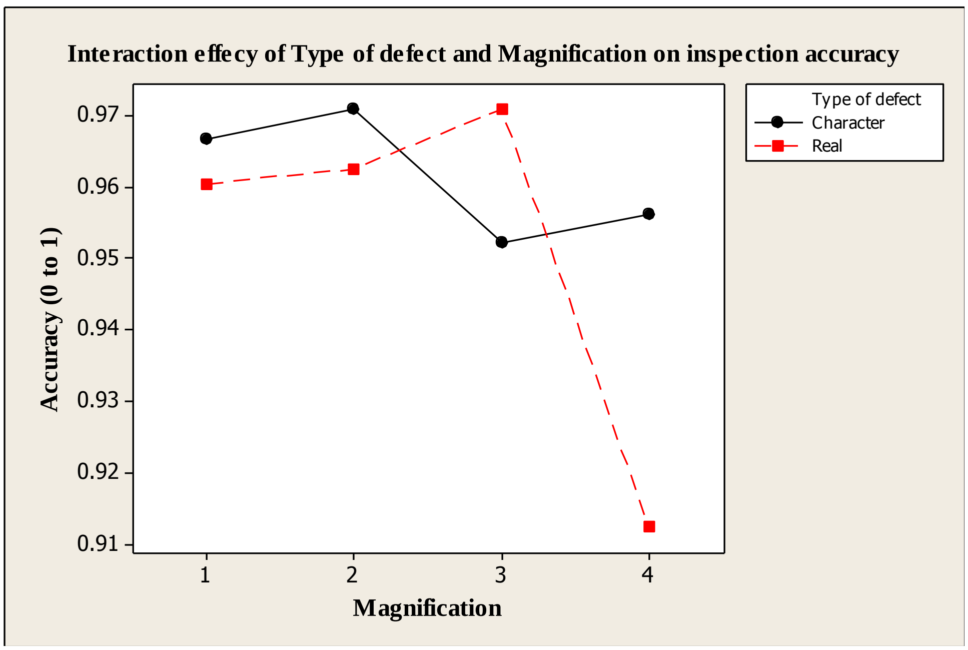



**Figure 5.6 Two – way interaction effects between Type of defect and Magnification**

It can be observed from the above plot that for magnification one and magnification two, the inspection accuracy for the character defect is more than the inspection accuracy for the real defect. For magnification three, the inspection accuracy for the real sample is more than the inspection accuracy for character sample. For magnification four, the inspection accuracy for character samples is more than the inspection accuracy for the real samples. The above mentioned observations can be confirmed by performing a Tukey test.

Intuitively, it can be assumed that the character samples will be easier to inspect at all magnifications as they are easier to go through and inspect. For magnification three it can be observed that the accuracy for the real samples was more than the accuracy for the character samples. This can be due to the influence of other factors such as density and Location of defect.

## 5.5 Results from regression analysis for magnification

A regression analysis was performed on the data to understand the relationship between magnification and time. The regression equations can be used to extrapolate the study to understand how the magnification would influence the time taken for inspection for micro-manufactured parts.

For the regression analysis, the mean values for each magnification level were used instead of the raw data. This was done to reduce the number of degrees of freedom and to provide a more accurate regression curve. The procedure used for the smoothing of the data is explained below.

Each subject inspects 16 samples for every one of the four magnifications (1, 2, 3, and 4) present in this experiment. The mean time taken for the 16 samples is used. This would result in four data points per subject. For 60 subjects, this would be 240 data points.

In the following sections, the regression equations obtained for the smoothened magnification-time data are described in detail.

### 5.5.1 Regression models for all four levels of magnification

Various regressive models were tested in this study using Minitab to find the best fit model to quantify the relationship between magnification and time. Table 6.1 shows a summary of all the regression models that were evaluated for the time taken vs. magnification data obtained from the visual inspection experiment.

**Table 5.7 Summary of various regression models for Magnification**

| Model | p-value for Magnification |
|---|---|
| $Y = a + bX$ | Not significant |
| $Y = a + bX + cX^2$ | Not significant |
| $Y = a + bX + cX^2 + dX^3$ | Not significant |
| $Y = a + bX + c(1/X)$ | Not significant |
| **$Y = a + b(1/X)$** | **Significant** |

Y denotes Time; X denotes Magnification; $p \leq 0.05$ significant

From the above table it can be observed that the linear model for time and magnification was shown to be not significant. Some other popular regression models such as cubic models and quadratic regression models were tested and proved to be not significant for the experimental data used for this study.

After the trial and error verification of above mentioned models, the Y = a + b*(1/X) model yielded a significant relationship between the time and magnification data considered for this experiment. The actual equation obtained from Minitab was:

$$Time = 3.52 + (1/Magnification)$$

This shows that time taken for visual inspection is inversely proportional to the magnification for the data obtained for this experiment. With an increase in magnification, there is a decrease in the time taken for visual inspection.

# Chapter VI
# Conclusions and Scope for future work

Human visual inspection is one of the most important means of maintaining process control in manufacturing processes. There has been extensive research performed on the factors that affect visual inspection performance for macro manufacturing.

In the recent years, there has been significant emphasis on Micro/Meso scale manufacturing and the process control for these processes. Visual inspection was identified as one the major means of process control for Micro/Meso scale manufacturing.

A lack of literature on manual visual inspection models that considered the effect of size on manual visual inspection for Micro/Meso scale parts prompted a need for this study. Since visual inspection is one of the major means of process control for micro manufacturing, it was postulated that such a study would help predict process control for Micro/Meso scale manufacturing.

A visual inspection experiment was developed which presented a combination of the major factors that effected manual visual inspection from the literature published over the years. The purpose of creating such an experiment was to mimic a real-time inspection scenario and obtain time and accuracy data that would help understand the size effects.

Efforts were made to develop a linear model for search time and magnification to help predict how increasing/decreasing magnification effects the search time of the inspector performing the inspection task.

## 6.1 Results from ANOVA

A two-way analysis of variance (ANOVA) was carried out in order to analyze the variations between the factors considered for this experiment. The analysis of variance was carried out separately for inspection time and accuracy.

The ANOVA results for inspection time indicated that the effects of type of defect and age were found as significant factors for the data collected from the visual inspection experiment. The mean inspection time was found to be higher for the more complex defect types. The young subjects took less time for inspection when compared to the older subjects.

These observations line up well with the published literature for macro visual inspection which identified both factors as critical for macro inspection. It can be noted that a reduction of size does not change the effect of these factors. An analysis of the significant interaction effect between magnification and density show that there is a strong effect of underlying factors in case of interaction effects.

The ANOVA results for accuracy indicate that magnification and age were significant factors in case of accuracy. The results from magnification indicate that too much magnification may not to be very beneficial for inspection processes.

75% magnification was identified as an optimum level of magnification for this study. Performing such an ANOVA prior to choosing a level of magnification might help industries to increase the accuracy of their human visual inspectors. In case of age, it was observed that younger subjects were more accurate than the older subjects.

One of the major objectives of this study was to develop a general linear relationship between inspection time and magnification to predict process control for Micro/Meso scale manufacturing. It was postulated that increasing magnification increased visual inspection performance and reduced search time whereas decreasing magnification would decrease visual inspection performance and increased search time.

From the results of the analysis of variance for time, it was identified that magnification was not identified as a significant factor. This indicates that the approach used for this experiment may not be a valid approach to model the general linear relationship between size effect and inspection time.

## 6.2 Results from regression

A regression analysis was performed to estimate the relationship between search time and magnification. Magnification was independent variable and the search time was the dependent variable for this regression analysis. Such an analysis would identify the nature of the relationship between search time and level of magnification for the data considered for this experiment.

Various regression models were tested by trial and error method to find a model that presented a statistically significant relationship between search time and level of magnification. It was observed that the relationship between magnification and search time is not linear for this study. The magnification was seen to be inversely proportional to the inspection time.

This indicates that with an increase in magnification there is a decrease in the time taken for inspection. However, since the magnification was not identified as a significant factor in the analysis of variance, this cannot be generalized for all inspection scenarios.

## 6.3 General discussion

Magnification was not identified as a significant factor in the analysis of variance for time. This indicates that this approach might not be valid to model the general relationship between magnification and inspection time in case of Micro/Meso scale manufacturing. The results from the regression analysis indicate that magnification is inversely proportional to search time from the data considered for this experiment. This indicates that for the data considered for this particular study, magnification played a beneficial role.

A more extensive study with more subjects and increased defect types may produce more accurate results to model the relationship between search time for inspection and the level of magnification for Micro/Meso scale manufacturing.

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