A vision system for surface roughness measurement.

Francis Luk
University of Windsor

Follow this and additional works at: https://scholar.uwindsor.ca/etd

Recommended Citation
https://scholar.uwindsor.ca/etd/6821

This online database contains the full-text of PhD dissertations and Masters' theses of University of Windsor students from 1954 forward. These documents are made available for personal study and research purposes only, in accordance with the Canadian Copyright Act and the Creative Commons license—CC BY-NC-ND (Attribution, Non-Commercial, No Derivative Works). Under this license, works must always be attributed to the copyright holder (original author), cannot be used for any commercial purposes, and may not be altered. Any other use would require the permission of the copyright holder. Students may inquire about withdrawing their dissertation and/or thesis from this database. For additional inquiries, please contact the repository administrator via email (scholarship@uwindsor.ca) or by telephone at 519-253-3000ext. 3208.
NOTE TO USERS

This reproduction is the best copy available.

UMI
A VISION SYSTEM FOR SURFACE ROUGHNESS MEASUREMENT

by

Francis Luk

A Thesis
Submitted to
the Faculty of Graduate Studies and Research
Through
the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science at
the University of Windsor

Windsor, Ontario, Canada

1987
INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.
ABSTRACT

The purpose of this research work was to develop an optical technique for the measurement of surface roughness for part quality inspection in a production environment. The system comprises a collimated 12W white light for light source and an optical system which captures the reflected light from a machined surface and images it onto a CCD camera. The analog signal from the camera is then digitized and analyzed by an IBM PC-AT. Two techniques were used in the study: one by the analysis of the grey-level histogram of the image and the other by the spectral analysis of a surface profile.

The characteristics of the system were first examined to obtain an optimal setting for the measurement. Several optical parameters were then derived to quantify the roughness and correlate with the mechanical surface roughness parameter Ra as obtained from a stylus instrument for tool steel specimens. It was found that the following parameters: SD/RMS, the maximum peak and the RMS level of a spectrum have good correlation with the mechanical surface roughness. This indicates that they can be used to characterize the roughness of machined surfaces. Similar results were obtained for brass and copper specimens. The results also indicated that the optical system has a better measurement precision over the stylus device because of the
advantage of area sampling over line sampling.

To simulate the measurement in a production environment, the specimens were immersed in a cutting fluid. Though the sensitivity of the system decreased, a similar trend was observed. The roughness assessment work was extended to the case where the surface contains flaws. To discriminate flaws from regular surface roughness (due to grinding), a simple algorithm was developed. This was based on the values of several statistical parameters which were derived from the grey level histogram.

In general, the system provides a fast and convenient way to assess the quality of a surface. The proposed system is a non-contact measuring device, therefore it is versatile and offers a much faster inspection speed than the traditional stylus devices.
ACKNOWLEDGEMENT

The author would like to thank Dr. V. M. Huynh for his guidance and support throughout the study. Thanks are also extended to Dr. W. North, Dr. J. Soltis and Dr. Z. Reif for their expertise and encouragement. Technical help from Mr. Doug Chang, Mr. Thomas Lau, Mr. George Ng, Mr. Peng Lim and Mr. Ming Lai is greatly appreciated. Also much thanks to Mr. R. Tattersall for his time on machining test specimens and to Mr. W. Beck for his time on the electronic work. Mr. Hugh Miller research assistance in summer 1986 is gratefully acknowledged.

This research is financially supported by the National Sciences and Engineering Research Council of Canada (NSERC) through grant number A5286.
Dedicated to
my parents
and sisters
CONTENTS

ABSTRACT .................................................... iii
ACKNOWLEDGEMENTS ............................................ v
TABLE OF CONTENTS .......................................... vii
LIST OF FIGURES ............................................. ix
LIST OF TABLES .............................................. xiii
NOMENCLATURE ............................................... xiv

Chapter page

I. INTRODUCTION .......................................... 1
   Concept of Surface Finish 3
   Surface Roughness Parameters 4
       Average Roughness - Ra 4
       RMS Roughness - Rq 4
       Maximum Peak to Valley Roughness - Rt 4
   Surface Roughness Measurement Techniques 5
       Contact Measurement 5
       Non-Contact Measurement 6
   Objectives 8

II. LITERATURE SURVEY .................................... 14
   Specular Reflectance 15
   Diffuseness 16
   Ellipsometry 17
   Speckle 17

III. EXPERIMENTAL APPARATUS .............................. 21
   Equipment Descriptions 22
   Test Samples 24
   Illumination schemes 25
       Configuration 1 25
       Configuration 2 25
       Configuration 3 25
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Definition of Tool Wear</td>
<td>9</td>
</tr>
<tr>
<td>1.2</td>
<td>A schematic diagram of the features on a surface</td>
<td>10</td>
</tr>
<tr>
<td>1.3</td>
<td>Definition of Average Roughness Ra</td>
<td>11</td>
</tr>
<tr>
<td>1.4</td>
<td>Definition of Maximum Peak to Valley Roughness Rt</td>
<td>11</td>
</tr>
<tr>
<td>1.5</td>
<td>A schematic diagram of a profilometer</td>
<td>12</td>
</tr>
<tr>
<td>1.6</td>
<td>(a) Diagram showing Bright field illumination</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>(b) Diagram showing Dark field illumination</td>
<td>13</td>
</tr>
<tr>
<td>2.1</td>
<td>Basic Scattering Geometry</td>
<td>19</td>
</tr>
<tr>
<td>2.2</td>
<td>A schematic diagram of surface roughness measurement by using laser speckle</td>
<td>20</td>
</tr>
<tr>
<td>3.1</td>
<td>A block diagram of the Dark field Experimental Setup</td>
<td>26</td>
</tr>
<tr>
<td>3.2</td>
<td>Arrangement of light source and camera</td>
<td>27</td>
</tr>
<tr>
<td>3.3</td>
<td>A photograph showing the system set-up</td>
<td>28</td>
</tr>
<tr>
<td>3.4</td>
<td>A photograph of the CCD Camera</td>
<td>29</td>
</tr>
<tr>
<td>3.5</td>
<td>A photograph of the microscope used in the measurement</td>
<td>29</td>
</tr>
<tr>
<td>3.6</td>
<td>A photograph of the Mitutoyo Surftest III Profilometer</td>
<td>30</td>
</tr>
<tr>
<td>3.7</td>
<td>A Close-up view of the measuring arm for the Mitutoyo Surftest III profilometer</td>
<td>30</td>
</tr>
<tr>
<td>3.8</td>
<td>a) Illumination Configuration 1</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>b) Typical image obtained by this set-up</td>
<td>31</td>
</tr>
<tr>
<td>3.9</td>
<td>a) Illumination Configuration 2</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>b) Typical image obtained by this set-up</td>
<td>32</td>
</tr>
<tr>
<td>3.10</td>
<td>a) Illumination Configuration 3</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>b) Typical image obtained by this set-up</td>
<td>33</td>
</tr>
</tbody>
</table>

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1.</td>
<td>Histogram distribution of tool steel specimens for different roughnesses</td>
<td>38</td>
</tr>
<tr>
<td>4.2.</td>
<td>Lighting fixture configuration</td>
<td>39</td>
</tr>
<tr>
<td>4.3.</td>
<td>Effect of grazing angles on scattering patterns of a tool steel sample Ra=0.2μm</td>
<td>40</td>
</tr>
<tr>
<td>4.4.</td>
<td>Effect of grazing angles on optical parameter for two different tool steel specimens</td>
<td>41</td>
</tr>
<tr>
<td>4.5.</td>
<td>Effect of grazing angles on optical parameter for two different brass specimens</td>
<td>42</td>
</tr>
<tr>
<td>4.6.</td>
<td>Effect of grazing angles on optical parameter for two different copper specimens</td>
<td>43</td>
</tr>
<tr>
<td>4.7.</td>
<td>Effect of optical filters on scattering pattern of a tool steel sample for a 5 degree grazing angle</td>
<td>44</td>
</tr>
<tr>
<td>4.8.</td>
<td>Effect of illumination distance on optical parameter for two different Tool Steel specimens</td>
<td>45</td>
</tr>
<tr>
<td>4.9.</td>
<td>A block diagram of the Fast Fourier Transformation algorithm</td>
<td>48</td>
</tr>
<tr>
<td>4.10.</td>
<td>Signal flow diagram of the data handling procedures</td>
<td>49</td>
</tr>
<tr>
<td>5.1.</td>
<td>Relation between optical parameter and ground surface roughness for tool steel specimens for configuration 1</td>
<td>55</td>
</tr>
<tr>
<td>5.2.</td>
<td>Relation between optical parameter and ground surface roughness for brass specimens for configuration 1</td>
<td>56</td>
</tr>
<tr>
<td>5.3.</td>
<td>Relation between optical parameter and ground surface roughness for copper specimens for configuration 1</td>
<td>57</td>
</tr>
<tr>
<td>5.4.</td>
<td>Relation between optical parameter and ground surface roughness for tool steel specimens for configuration 2</td>
<td>58</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>5.5.</td>
<td>Relation between spectrum RMS and ground surface roughness for tool steel specimens for configuration 1</td>
<td>65</td>
</tr>
<tr>
<td>5.6.</td>
<td>Relation between spectrum maximum peak and ground surface roughness for tool steel specimens for configuration 1</td>
<td>66</td>
</tr>
<tr>
<td>5.7.</td>
<td>Relation between spectrum RMS and ground surface roughness for tool steel specimens for configuration 2</td>
<td>67</td>
</tr>
<tr>
<td>5.8.</td>
<td>Relation between spectrum maximum peak and ground surface roughness for tool steel specimens for configuration 2</td>
<td>68</td>
</tr>
<tr>
<td>5.9.</td>
<td>Relation between optical parameter and ground surface roughness for tool steel specimens immersed in oil</td>
<td>71</td>
</tr>
<tr>
<td>5.10.</td>
<td>Correlation curves for oil-free and oil-immersion conditions</td>
<td>72</td>
</tr>
<tr>
<td>5.11.</td>
<td>An original image of a machined surface contains flaws</td>
<td>77</td>
</tr>
<tr>
<td>5.12.</td>
<td>The threshold image of figure 5.11</td>
<td>77</td>
</tr>
<tr>
<td>5.13.</td>
<td>Template matching arrays</td>
<td>78</td>
</tr>
<tr>
<td>5.14.</td>
<td>Calculations procedure of template matching</td>
<td>79</td>
</tr>
<tr>
<td>5.15.</td>
<td>The resulting image after a horizontal edge detection is performed on the original image</td>
<td>80</td>
</tr>
<tr>
<td>5.16.</td>
<td>(a) Histogram distribution for a normal surface</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>(b) Histogram distribution for a damaged surface</td>
<td>81</td>
</tr>
<tr>
<td>5.17.</td>
<td>(a) A photograph of a normal ground surface</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>(b) The histogram of the image shown in 5.17(a)</td>
<td>82</td>
</tr>
<tr>
<td>5.18.</td>
<td>(a) A photograph of a surface contains a medium size flaw</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>(b) Histogram of the picture shown in 5.18(a)</td>
<td>83</td>
</tr>
<tr>
<td>5.19.</td>
<td>(a) A photograph of a surface contains a large size flaw</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>(b) Histogram of the picture shown in 5.19(a)</td>
<td>84</td>
</tr>
</tbody>
</table>
5.20. (a) A photograph of a surface containing distributed flaws ........................ 85
(b) Histogram of the picture shown in 5.20(a) ........ 85
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1.</td>
<td>Correlation Equations for different materials</td>
<td>59</td>
</tr>
<tr>
<td>5.2.</td>
<td>Repeatability of the optical parameter measurement results</td>
<td>60</td>
</tr>
<tr>
<td>5.3.</td>
<td>Repeatability of the stylus measurement results</td>
<td>61</td>
</tr>
<tr>
<td>5.4.</td>
<td>Ra values obtained for a ground Tool Steel surface using a mitutoyo surftest III profilometer</td>
<td>62</td>
</tr>
<tr>
<td>5.5.</td>
<td>Ra values obtained for the same ground surface (as Table 5.4) by use of the optical system and calibration curve</td>
<td>63</td>
</tr>
<tr>
<td>5.6.</td>
<td>Correlation Equations of the Measurements by using RMS and Max. Peak Methods</td>
<td>69</td>
</tr>
</tbody>
</table>
NOMENCLATURE

$\Theta$ = grazing angle
$\alpha_3$ = coefficient of skewness of the greylevel distribution
$\alpha_4$ = kurtosis value of the greylevel distribution
$D$ = illumination distance
$F_i$ = number of pixels at greylevel $X_i$
$F_S$ = spatial frequency of the first order feed component
$FSO$ = full scale output
$L$ = assessment length
$N$ = total number of pixels in the greylevel distribution
$P$ = the resulting product of two matrix multiplication
$R$ = optical roughness parameter (SD/RMS)
$Ra$ = average surface roughness ($\mu m$)
$Rq$ = RMS surface roughness ($\mu m$)
$Rt$ = maximum peak to valley roughness ($\mu m$)
$RMS$ = root mean square height of the greylevel distribution
$SD$ = standard deviation of the greylevel distribution
$T$ = predetermined threshold value
$W_i$ = template coefficients ($i = 0, 1, ..., 9$)
$\bar{X}$ = mean value of the greylevel distribution
$X_i$ = greylevel coordinates ($i = 0, 1, ..., 255$)
$y(x)$ = ordinate of the profile curve
Chapter I

INTRODUCTION

During the last decade, there has been an increased interest in surface roughness measurement as we are more aware of the important role of the surface structure in the performance of machined parts. Proper control of surface roughness not only can minimize the production cost by not overspecifying the surface quality but also can prolong the lifetime of a workpiece. The following are some examples where surface finish are critical to the functional behaviour and performance of a mechanical surface [1]:

a) gage blocks.

b) Surface preparation for subsequent painting, adhesives, plating, etc.

c) Surfaces which must operate with seals, o-rings, piston rings, etc.

d) Antifriction bearing surfaces, journal bearings, gears, etc.

Surface roughness can have both minimum and maximum limits as in the case of a journal bearing of an electric motor. At some level lubrication action in the journal bearing decreases as surface roughness becomes better (lower Ra value), hence it is important to set a lower limit of surface roughness. If however, the roughness goes above Ra = 0.45 µm, premature bearing failure
occurs.

The control of surface roughness is desirable not only for quality control, but also for monitoring the condition of a machine tool in operation. During machining, the main factors which affect the surface roughness of a workpiece are tool geometry, feed rate, material properties, spindle rotational errors and chatter vibration [2]. Under ideal conditions, the surface roughness profile of a machined part is normally determined by the tool geometry and the feed rate.

In practice, the tool is not ideally positioned relative to the workpiece. There are spindle rotational errors and chatter vibration, which cause a relative displacement between the tool and the workpiece. This in turn leads to a modification of the surface roughness profile. This modification will show up as error components in the roughness spectrum. Thus, by analyzing the amplitude of the error components, the working conditions of a machine can be evaluated.

It is also known that in a cutting process, the machined surface roughness Ra increases as the tool wear progresses [3]. In this case, the tool wear is defined as flank wear and nose wear as shown in Figure 1.1. It has been shown that high correlation exists between tool wear and the machined surface roughness especially for nose wear in a constant feed rate machining process. Therefore by knowing the machined surface roughness, one can estimate the extent of tool wear. A knowledge of tool wear can improve productivity by allowing lead time to replace the tool and/or using the tool to the end of its useful
1.1 Concept of surface finish

Surface profile consists of roughness, waviness and flatness. Among those factors which define the surface structure, the roughness is a quantity that would contribute to the feeling such as "smooth" or "rough".

The contour given by sectioning a finished surface perpendicular to the lay direction (or direction of machining) is called the "real profile curve", from which waviness and flatness are excluded to obtain the "roughness curve". These characteristics of a surface are briefly described as follows (see Figure 1.2):

Lay: it is the machine feed marks left on the surface by a cutter or grinder in a machining or grinding operation. The lay frequency is determined by the feed rate or the grade of the grinding wheel.

Waviness: it represents the low frequency (long wavelength) component which is normally identified as the basic frequency of the surface.

Roughness: it is defined as the finely-spaced surface irregularities that appear in a consistent pattern, which are produced by machining.

Surface flaws: they are irregularities that do not appear in a consistent pattern, such as porosity pits, dents and cracks.
1.2 Surface Roughness parameters

The most commonly used roughness parameters are average roughness, rms roughness and maximum peak to valley roughness.

1.2.1 Average Roughness - Ra

Ra is the universally recognized parameter of roughness for metal surfaces. It is the arithmetic mean (AA) of the absolute values of the surface profile. The center line is drawn in such a way that the total areas of the profile above and below it are equal (Figure 1.3).

Mathematically, the average roughness is expressed as:

\[
Ra = \frac{1}{L} \int_0^L |y(x)| \, dx \quad (1.1)
\]

where \( y(x) \) is the ordinate of the profile curve

\( L \) is the assessment length.

1.2.2 RMS Roughness - Rq

Mathematically, the RMS roughness is expressed as:

\[
Rq = \sqrt{\frac{1}{L} \int_0^L y^2(x) \, dx} \quad (1.2)
\]

where \( y(x) \) and \( L \) are defined as above.

1.2.3 Maximum Peak to valley Roughness - Rt

This is the distance between the highest peak and lowest valley in the prescribed sampling length \( L \), (see figure 1.4).
1.3 Surface Roughness Measurement Techniques

Surface roughness instruments currently used in the manufacturing industry can be divided into two main groups: contact and non-contact.

1.3.1 Contact Measurement

The most commonly used surface roughness instrument are stylus devices [4,5]. These devices electronically correlate the motion of a diamond-tipped stylus to the roughness of the surface under investigation. A typical profilometer is shown in Figure 1.5. The radius of the stylus is in between 400 to 500 microinches (10 to 12 μm). The vertical movements of the stylus are transmitted to a coil inside the tracer body. In this motion, the coil breaks the flux of a permanent magnet to produce a small fluctuating voltage whose magnitude is directly proportional to the height of the surface profile. A graphical device can be connected to the profilometer to generate a magnified surface profile. Even though, international standards are defined in terms of measurements made by the profilometer, this instrument suffers from the following disadvantages:

a) Speed: The main disadvantage is the slow measurement speed which ranges from 2 mm/s to 6mm/s. Because it is a time consuming process, only a very limited sample of measurement can be made in a typical production environment. Statistical quality control based on such measurements yields a low confident level. This can result in substantial scrap if the surface finishing process deteriorates without being detected. In addition, the
measurement requires a direct physical contact with the parts which may cause unnecessary damage.

b) Repeatability: The stylus-instrument measures along a line, and different lines may yield different results. This lack of repeatability can be critical in cases where close control on surface finish is required.

With the increased use of machine automation in industries, it is necessary for the control system to provide real time feedback on the quality of the machined surface. Therefore, a new kind of instrument is needed for the in-process measurement of surface roughness.

1.3.2 Non-Contact Measurement

An alternative for roughness measurement are optically based systems. These systems process a small area a time at a reasonable speed. Two illumination techniques are used for roughness measurement: bright field and dark field illumination, see figure 1.6.

The main advantage of the optical method is the non-contact property which makes it suitable for use in almost any industrial environment. Secondly as there is no moving parts in optical systems, wear out problems are eliminated. Furthermore, the optical method inspects an area rather than just a line, hence it can produce a better repeatability. Most important of all, an optical system is potentially much faster than the stylus instrument and thereby can achieve a faster inspection speed.
Most of the existing optical systems use coherent light for illumination and a linear diode array for sensing the reflected signal [6,7]. The main drawbacks of using coherent light sources are that they are expensive and the range of measurement is limited. A new method of surface roughness measurement is required to overcome the above disadvantages.
1.4 Objectives

The main objective of this work is to develop an optical measuring system to quantify surface roughness. This optical measuring system comprises an incandescent white light source for illumination, a CCD camera to capture the reflected light through a microscopic imaging system and a micro-computer system to process and analyse the image.

Three incident light paths will be investigated in the study, namely, perpendicular, normal and parallel to the lay direction. Each incident light path yields different light scattering patterns on the surface, and measurement procedures will be developed to analyse these patterns.

From the results of these measurements, descriptors will be selected to characterize the machined surface roughness Ra for surfaces finished by grinding.

These descriptors will be calibrated against a mechanical stylus roughness measuring device in order to evaluate the system.

The presence of surface flaws will also be investigated using the above mentioned optical set-up.
Figure 1.1 Definition of Tool Wear
Figure 1.2 A schematic diagram of the features on a surface
Figure 1.3 Definition of Average Roughness $Ra$

Figure 1.4 Definition of Maximum Peak to Valley Roughness $Rt$
Figure 1.5 A schematic diagram of a profilometer
Figure 1.6 (a) Diagram showing Bright field illumination  
(b) Diagram showing Dark field illumination
CHAPTER II
LITERATURE SURVEY

The operation of the optical roughness measuring system is generally based on the principle of light scattering. According to this theory, when a beam of coherent light such as laser is reflected from a metal surface, the radiation is scattered into an angular distribution governed by Snell's law. This is shown in Figure 2.1. For very smooth surface, the pattern of scattered radiation is localized around the specular direction with most of the energy propagating in specular direction. As the surface roughness increases, the intensity of the specular beam decreases while that of scattered radiation increases and becomes more diffuse. The angular distribution of diffuse radiation consists of a grainy fine structure called speckle which shows up as intensity contrast between neighbouring points in the scattered field. Another effect is that the light wave undergoes a polarization change upon reflection from the surface. All these phenomena, the intensity in the specular direction, the diffuseness of the angular pattern, the speckle contrast and the change in polarization are utilized for the development of surface roughness measuring instrument.

The theory of scattering of electromagnetic radiation from rough surfaces has been developed by several authors [8,9], applicable to both periodic and random rough surfaces. The most
comprehensive development of this work is given by Beckmann [8] who formulated the theory of specular and diffused reflection to derive the angular distribution of intensities in specular and other directions. In general, the light reflected into the specular direction gives information about the variance of surface height, while that scattered away from the specular direction depends, in addition, on the surface slopes.

a) Specular Reflectance

The specular reflectance method was originally developed by Bennett and Porteous [10] for studying the surface roughness. It is based on the inverse correlation between the specular reflectance and $Ra$ for normal incident. Other studies [11,12] on the same topic also show similar results. However, this method was found suitable only for surfaces having roughness values of 0.5$\mu$m or less and where the surface height distribution was approximately Gaussian in nature.

The work of Vashisht and Radhakrishnan [13] indicated that the correlation between the roughness and specular reflection does not hold in all cases. This problem is overcome by measuring the specular intensity for several angles of incidence [14]. The results from this method show excellent correlation between the roughness values derived from their optical measurements and those measured by stylus instruments. It is conceivable that this method could be adapted for on-line measurement where several detectors are used to receive the specular reflection from different light sources incident at different angles.
b) Diffuseness

This method relies on the fact that the pattern of scattered radiation becomes more diffuse with increasing surface roughness. Jasson, Rourke and Bell [15] used a 64 element linear lead-selenide array to detect the reflected signal from a modified 3.39 micron wavelength helium-neon laser. The detector covers an area of 23 degrees from the specular direction. An exponential function was found to give the best correlation between the intensity ratio of the specular beam and the reflected beam, and the machined surface roughness Ra measured by a stylus device. This is applicable in the roughness range of 0.05 to 0.5 microns.

Similar observation was reported by K.J. Stout [16]. In his study, a photo-diode was used to detect the reflected light from an infrared emitter off a ground surface. The operation involves pulsing an infrared light at low incidence angles to the surface under test. The light path of the probe was positioned at right angles to the lay of the machined surface. An exponential relationship was found between the intensity of scattered light and the surface roughness Ra.

Recently, North and Agarwal [17] used a pair of fiber-optics to transmit laser light back and forth from a ground surface for roughness measurement. The ratio of the scattered radiation at 30 degree from the surface normal to the incident light was found to be an exponential function of the mechanical roughness Ra.
c) Ellipsometry

Ellipsometry consists in measuring the change in the polarization state of a beam of light when it is reflected from a surface. However, as the phenomena is not well understood, no conclusive trend was established yet [18-20]. Further study is needed to determine if such property can be sucessfully used to quantify surface roughness.

d) Speckle

Using laser speckle to measure surface roughness has been investigated by a number of workers [21-23]. This method involves the study of the contrast of speckle pattern in the scattered field when a coherent light is reflected from a metal surface. A schematic diagram of the experimental arrangement is shown in Figure 2.2. A laser light is reflected by the Mirror M and expanded by an inverted telescope $L_x$, to uniformly illuminate an aperture $P_1$. The transmitted light is focussed by a lens $L_o$ onto the surface $P_2$ which is moving along the direction as shown. The scattered light yields a speckle pattern in the far field. The pattern intensity is considered as a function of time and is measured by the photomultiplier $P_m$ through a small aperture $P_s$. The photomultiplier output is fed into the signal analyzing system to calculate the average contrast $V$ of the speckle intensity variation. The maximum speckle contrast yields a linear correlation with $R_a$. Good correlations were found for surfaces produced by different processes, namely machining, lapping and polishing.
Among these four techniques, specular reflectance and speckle contrast seems to be the most promising techniques for the future development of optical system for surface roughness measurement.
Figure 2.1 Basic scattering geometry
Figure 2.2 A schematic diagram of surface roughness measurement by using laser speckle.
CHAPTER III
EXPERIMENTAL APPARATUS

The apparatus used in the experiment is shown in Figure 3.1. It comprises a collimated 12W white light to illuminate the surface of interest. A solid state camera with a microscope optical system captures the reflected light from the surface. The analog signal from the camera is then transferred to a frame grabber board which digitizes the signal to an image of 512x512x8 bits of pixels. The digitized image is stored in one of the four frame buffers (available on the frame grabber board) for subsequent analysis by an IBM PC-AT. The frame grabber board uses the PC-AT bus and is capable of image capturing and digitization in 1/30 second. The microcomputer is equipped with a 512K RAM, a math co-processor, a 40 MByte hard drive and double floppy drives. Provisions are made to display the pre-processing/post processing image on a black and white video monitor which has a resolution of 800 x 600 pixels. A dot matrix printer and a plotter are connected to the microcomputer to provide hard copy outputs.

For the first part of this work, a lighting fixture was designed to adjust the illumination angle and the illumination distance, see Figure 3.2. The light source can be inclined in the x-y plane at an angle θ from the x-axis, this angle is known as the grazing angle. The distance between the light source and
the surface can also be adjusted, so as to determine the optimal setting for the system. In roughness measurement, the specimen is oriented in such a way that the lay direction is always along the z-axis. The scattering pattern of the surface is observed by a CCD camera positioned along the y-axis (the surface normal). The standoff of the camera is governed by the microscope lens used in the study. A larger standoff can be achieved by using a microscope lens with smaller magnification. In this study, a magnification of 50 was used. This resulted in a 20mm standoff, a field of view of 2mm square and a depth of field of approximately several microns. A photograph of the system setup is shown in Figure 3.3.

3.1 Equipment Description

The following section briefly describes the equipment used in this work, for further details see Appendix I.

a) Camera - A solid state (CCD) camera shown in Figure 3.4 is used to capture the reflected light intensity from the inspecting surface. The specifications of the CCD camera is listed as follows:

Specifications:

- Pickup device: Interline-transfer CCD
- Picture elements: 384 x 491 (h/v)
- Sensing area: 8.8mm x 6.6mm
- Pixel size: 23µm x 13.4µm (h/v)
- Signal system: EIA standards RS170
- Scanning system: 525 lines
  2:1 interlace
  30 frames/sec
Minimum illumination 3 lux (0.3 footcandles)
Sensitivity 400 lux (40 footcandles)
Signal-to-noise ratio Better than 45 dB
Power requirements Camera module + power unit: 12V DC, 10 to 200mA typ.
Vibration resistance 7G(11Hz to 200Hz)
Shock resistance 60G
Dimensions 44 x 29 x 72.5mm(w/h/d)
Weight 122 grams (4.3 ounces)

b) Imaging Board - A image digitizer is required to digitize the incoming analog signal from the camera for processing by a computer. Image digitizers are specified by the number of pixels (size of an image) and the number of bits in one pixel (greylevel scale). More pixels in an image results in higher resolution, and more grey scale results in a better representation of an image. In this work, the image digitizer is a PIP-1024 made by Matrox Corporation. The specifications of the imaging board are listed below:

Specifications:

**Frame Grabber**
* Resolution 512 x 512
* Bits/pixel 8
* Input Lookup Table 8 bits in/8 bits out
  8 software selectable maps

**Frame Buffer**
* Image Store one 1024 x 1024 buffer
  or four 512x 512 buffers
Display Unit

* D/A convertors
  Three 8 bit D/A convertors for RGB color output

* Color Lookup Table
  256 colors or intensities from a palette of 16.7 million colors
  8 software-selectable maps.

Dimensions

* Length
  335.30 mm

* Width
  106.77 mm

* Height
  32.70 mm

c) Microscope - Since the surface roughness is in the range of microns, a microscope optical system is required to magnify the image. The microscope optical system used in the study is Unitron model RM2 565 (shown in Figure 3.5).

b) Light source - A collimated 12W white light source is used to illuminate the surface of a specimen. The aperture of the light source can be adjusted to provide a specified illumination area.

e) Profilometer - The Mitutoyo Surftest III profilometer (shown in Figure 3.6) is used in this study to measure the roughness of the test specimens. Further information on the profilometer can be found from the operating manual [24].

3.2 Test Samples

Test samples used in this work were made of tool steel, brass and copper. They were machined using different grades of grinding wheels to produce various roughness. Their roughness ranges from
0.1 to 1.2 microns, see Appendix II. The mechanical and chemical properties of these materials are shown Appendix III.

3.3 Illumination schemes

In practical applications, parts to be measured are not accessible in a certain approach. To take this into account, the following illumination configurations were used in the study:

3.3.1 Configuration 1

This is the dark field illumination set-up where the incident ray and the surface normal are perpendicular to the lay direction as shown in Figure 3.8a. The camera optical axis is along the normal to the surface. A typical image obtained from this configuration is shown in Figure 3.8b.

3.3.2 Configuration 2

This is the bright field illumination arrangement. The light source is directed to the surface by a 45 degrees beam splitter at 90 degrees angle. The reflected specular beam (which is normal to the surface) passes through the beam splitter and is captured by the camera. The illumination plane formed by the incident and the reflected beams is parallel to the lay direction as shown in Figure 3.9a. A typical image obtained from this configuration is shown in Figure 3.9b.

3.3.3 Configuration 3

This set-up is similar to configuration 1 except the lay direction is on the same plane defined by the incident ray and the surface normal as shown in Figure 3.10a. A typical image obtained from this configuration is shown in Figure 3.10b.
Figure 3.1 A block diagram of the Dark Field Experimental set-up.
Figure 3.2 Arrangement of light source and camera
Figure 3.3 A photograph showing the system set-up.
Figure 3.4 A photograph of the CCD camera.

Figure 3.5 A photograph of the microscope used in the measurement.
Figure 3.6 A photograph of the Mitutoyo Surftest III profilometer.

Figure 3.7 A close-up view of the measuring arm for the Mitutoyo Surftest III profilometer.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 3.8(a) Illumination configuration 1.

Figure 3.8(b) Typical image obtained from the above configuration.
Figure 3.9(a) Illumination configuration 2.

Figure 3.9(b) Typical image obtained from the above configuration.
Figure 3.10(a) Illumination configuration 3.

Figure 3.10(b) Typical image obtained from the above configuration.
CHAPTER IV
MEASUREMENT PROCEDURES

Two measurement techniques were developed to analyse the image of a surface obtained by the optical system. They were:

a) Histogram analysis

b) Spectral analysis

The measurement procedures of these two techniques are discussed in the following sections.

4.1. Histogram Analysis

Histogram Analysis involves the analysis of the light scattering pattern from a machined surface from which statistical parameters are derived to quantify the surface roughness Ra. In this study, the scattering pattern is represented by the grey-level histogram which is a plot of frequency (number of pixels) versus light intensity. It can be shown that the scattering pattern of a machined surface is unique for a given material produced by a particular machining process, hence, it can be considered as the characteristics or signature of a surface. Figure 4.1 shows the histograms of tool steel samples which are ground to different roughnesses. It can be seen that as the roughness increases, the mean value and the spread of the distribution increase while the height of the distribution decreases. This indicates that the light scattering effect is
greater for rough surfaces. Since the spread and the height of the distribution have opposite trends, their ratio can be used to correlate to the surface roughness parameter $R_a$, which gives more sensitivity to a given change in roughness. This ratio is defined as the optical roughness parameter:

$$R = \frac{SD}{RMS} \quad \quad \quad \quad \quad \quad (4.1)$$

where:

$SD = $ standard deviation of the distribution and

$RMS = $ root mean square height of the distribution

The numerical calculations for these parameters were performed as follows:

$$SD = \left[ \sum_{i=0}^{255} F_i \left( X_i - \bar{X} \right)^2 / N \right]^{1/2} \quad \quad \quad \quad \quad \quad (4.2)$$

$$RMS = \left[ \left( \sum_{i=0}^{255} F_i^2 \right) / N \right]^{1/2} \quad \quad \quad \quad \quad \quad (4.3)$$

where:

$$\bar{X} = \left( \sum_{i=0}^{255} F_i X_i \right) / N$$

$$N = \sum_{i=0}^{255} F_i = (512)^2$$

$$X_i = $$ light intensity expressed in greylevel scale, $i = 0 \ldots 255$

$$F_i = $$ number of pixels at grey level $X_i$ as determined from the histogram.

4.1.1. Effect of Illumination Angle

To study the effect of illumination angles on the scattering pattern and consequently on the optical parameter, the grazing angle of the light source (shown in Figure 4.2) was altered while maintaining a constant illumination distance.
Figure 4.3 shows the scattering pattern of a smooth tool steel surface illuminated at different grazing angles. It can be seen that the intensity distribution becomes more spread out at higher grazing angles. This is due to the fact that at higher grazing angles, the camera axis is closer to the direction of specular reflection.

To determine the measurement sensitivity, roughness measurements were made on two tool steel samples: one smooth (Ra = 0.2 \mu m) and the other relatively rough (Ra = 1 \mu m) at different grazing angles and the results are shown in Figure 4.4. It can be seen in this figure that for the rough surface the measured R value decreases rapidly as the grazing angle increases while for the smooth surface, the R value changes only slightly. The greatest difference in the roughness values between the two samples is obtained at 5 degrees. Similar results were obtained for brass and copper specimens as shown in Figures 4.5 and 4.6. Thus to obtain greatest sensitivity, the grazing angle is kept at 5 degrees which is the practical minimum limit.

4.1.2. Effect of Illumination Intensity

The effect of various optical filters on optical roughness measurement for a 5 degree grazing angle is shown in Figures 4.7. It can be seen that the distribution shifts to the left as the illumination intensity decreases. Similar tests were performed with varying light intensity by changing the light-to-object distance. The results for the two tool steel samples are shown in Figure 4.8. As can be seen from this figure, a higher
measurement sensitivity can be achieved at reduced illumination.

From the above observation, a setting of 5 degree grazing angle and approximately at an illumination distance of 10 cm. was used for the subsequent calibration of the system.
Figure 4.1 Histogram distribution of tool steel specimens for different roughnesses

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 4.2 Lighting fixture configuration

\[ \theta = \text{GRAZING ANGLE} \]
\[ D = \text{ILLUMINATION DISTANCE} \]
Figure 4.3 Effect of grazing angles on scattering patterns of a tool steel sample Ra = 0.2µm
ROUGHNESS VS. GRAZING ANGLES

TOOL STEEL

Figure 4.4 Effect of grazing angles on optical parameter for two different tool steel specimens

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 4.5 Effect of grazing angles on optical parameter for two different brass specimens

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
ROUGHNESS VS. GRAZING ANGLE

COPPER

ROUGHNESS PARAMETER R (SD/RMS)

GRAZING ANGLE (DEGREES)

□ SMOOTH SURFACE + ROUGH SURFACE

Ra = 1 μm

Ra = 0.2μm

Figure 4.6 Effect of grazing angles on optical parameter for two different copper specimens

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 4.7 Effect of optical filters on scattering pattern of a tool steel sample for a 5 degree grazing angle.
Figure 4.8 Effect of illumination distance on optical parameter for two different tool steel specimens.
4.2. Spectral Analysis

Spectral Analysis has been used frequently in the analysis of surface roughness [25]. This technique involves the transformation of signals from one domain to another domain, for example from time to frequency. This transformation is normally done via a fast fourier transform algorithm which is a mathematical approach that divides a signal into its frequency components as shown in Figure 4.9. The input signals can either be in time domain or in spatial domain. Time domain signal is a record of the system output versus time, while, the spatial domain signal is a record of the system output versus distance. In the present study, the signal obtained is in spatial domain.

4.2.1. Definition of Spectral Analysis

Spectral analysis refers to the examination of the whole, or portions of the spatial frequency spectrum. In this study, the output from the vision system is a spatial record, therefore the transformation of this record is in spatial frequency domain. The y-axis of the spatial frequency spectrum represents the light intensity value and the x-axis represents the spatial frequency in terms of the inverse of a unit length ($\text{mm}^{-1}$). Thus, the spectrum represents the light intensity value at a given spatial frequency.

There are several ways to analyze a spectrum. One way is to examine the intensity value at a particular spatial frequency, that is to analyze the peak. This is useful for tracing the development of tool wear or geometric defect in production tools.
during the machining operation [25]. Another way is to determine the RMS level of the spectrum. This can be done for the whole spectrum or between two particular spatial frequencies (frequency band). This integration yields an equivalent RMS energy level of the specified spatial frequency range which is an additional parameter that can be used to indicate the roughness of a surface. Both methods are used in this work.

4.2.2. Data Handling

To generate a spatial record, an area scan is first performed on the two-dimensional image captured by the vision system to give a one-dimensional surface profile. The resulting data is then averaged to yield an equivalent line-scan profile which is referred to as the spatial record. To reduce sampling errors, a Hanning window function is applied to the spatial record to essentially give more weight to the data located near the center of the record. The windowed spatial record is then passed through a high pass filter to attenuate the basic frequency which characterizes the waviness of a surface. Finally, the Fast Fourier Transform algorithm developed by Cooley and Tukey [26] is used in this work to convert the filtered signal from the spatial domain to the spatial frequency domain. The data is now in a suitable form for analysis to assess the quality of the surface. The block diagram of the data handling procedure is shown in figure 4.10. The flowcharts and computer programs used to perform histogram and spectral analysis are illustrated in Appendix IV.
Figure 4.9 A block diagram of the Fast Fourier Transform algorithm.
Figure 4.10 Signal flow diagram of the data handling procedures.
Measurements were made on different samples of tool steel, brass and copper to derive the values of the roughness descriptors as defined earlier. These were then compared with the mechanical roughness measurements made by the profilometers. The procedure was then repeated for different illumination configurations. Some observations were also made regarding the criteria for use in detecting surface flaws.

5.1 Histogram Analysis

The roughness descriptor derived from the histogram analysis is the parameter SD/RMS. To determine this parameter, measurements were made on tool steel samples using configuration 1. The results were correlated to the mechanical roughness Ra as shown in Figure 5.1. A correlation curve was obtained using a least square fit. It can be seen that this curve is almost linear up to Ra = 0.5 μm. Beyond that, the slope of the curve decreases with increasing Ra. Measurements were then repeated for brass and copper specimens under the same configuration and their corresponding correlation curves are shown in Figures 5.2 and 5.3. For these two materials, the correlation curves are quite similar. In the roughness range of 0.2 to 1.6μm, the two curves are linear, even though of different slopes.
In a comparison between tool steel and brass (Figures 5.1 and 5.2) one can recognize that their correlation curves have different characteristics. This may due to the fact that tool steel and brass have different modes of tearing and fracture during grinding which may give rise to a different type of surface profile. Consequently, the optical correlation curve for a given material is unique and may be related to the machinability of the material. This result agrees with that obtained by Ng [27].

The pertinent data relating to the correlation process are presented in Table 5.1. In this table, the standard error is a measure of dispersion of data points about the fitted line while the correlation coefficient determines the degree of dependency between the variables. The correlation coefficients for most correlation curves are greater than 90%.

For tool steel, a power function was found to give the best fit in the roughness range of 0.1 to 1 um. The power function is in the form of

$$R = a \cdot Ra^{0.5} + b \quad \quad \quad \quad (5.1)$$

where $R$ = roughness parameter

$Ra$ = average roughness $Ra$ in um.

$a$ and $b$ are constants.

For brass and copper specimens, it was found that a linear function has the best correlation to the experimental data. This linear function is of the form:

$$R = a \cdot Ra + b \quad \quad \quad \quad (5.2)$$
where \( R \) = roughness parameter

\[ Ra = \text{average roughness in } \mu\text{m}. \]

\( a \) and \( b \) are constants.

The measurement procedures were repeated for illumination configuration 2. The correlation curve shown in Figure 5.4 indicates that the roughness parameter is inversely proportional to the average roughness \( Ra \).

For illumination configuration 3, the contrast in the image was very low and therefore no meaningful measurement was obtained.

5.1.1. Measurement Repeatability

The repeatability of the measurement was examined by taking ten readings on the same surface. The surfaces used were consisted of tool steel specimens which were ground to different roughnesses (0.1 - 0.7 \( \mu\)m). The results obtained for configuration 1 are presented in Table 5.2. The largest variation obtained for any numerical assessment is approximately 19\%, with an average variation of 11\%. The measurement process was repeated by using a stylus instrument. Ten readings were obtained on the same surface and the results were presented in Table 5.3 for comparison. For the stylus instrument, the largest variation obtained for any numerical assessment is approximately 15\%, with an average variation of 9\%. Thus, both instruments has similar degree of repeatability.

To compare the precision of the measurements made by a stylus instrument and the proposed optical system, roughness measurements were made at ten different zones on a roughness
specimen which was ground to a roughness of 0.51μm. The optical roughness parameter R obtained by the proposed system was then converted to the average roughness Ra using the established calibration curve. Similar measurements were made using the stylus instrument and the results from both methods of measurement are shown in Tables 5.4 and 5.5 for comparison.

The results obtained from the two measurement processes give similar mean values:

**Stylus:**  \( Ra = 0.505 \mu m \)

**Optical system:**  \( Ra = 0.52 \mu m \).

The difference between the two results is small. For 10 readings, the precision of the optical method is 6.7%, compared to 15% for the stylus method.

Thus the proposed optical technique gives more consistent readings than the conventional stylus method. This is due to the fact that the former is based on an area sampling process which tends to give less variation in the results as compared to the line sampling.

5.1.2. Measurement Error

The error of an instrument indicates the deviation of a reading from a known input. To assess the measurement error of the proposed technique, the optical readings were compared to the readings obtained through the use of correlation curves. For tool steel specimens, the maximum error of measurement was found to be 8.1% full scale output (FSO) with an average error of 3.8% FSO. For brass and copper specimens, the maximum error of
measurement were found to be 17.3% FSO and 5.9% FSO. Thus, the correlation curve for the copper specimens has the least measurement error, while for brass is the worst.
Figure 5.1 Relation between optical parameter and ground surface roughness for tool steel specimens under configuration 1.
Figure 5.2 Relation between optical parameter and ground surface roughness for brass specimens under configuration 1.
Figure 5.3 Relation between optical parameter and ground surface roughness for copper specimens under configuration 1.
Figure 5.4 Relation between optical parameter and ground surface roughness for tool steel specimens under configuration 2.
Table 5.1 Correlation Equations for different materials

<table>
<thead>
<tr>
<th>Roughness Range</th>
<th>Material Type</th>
<th>Correlation Equations</th>
<th>Standard Errors of Estimate</th>
<th>Coefficient of Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.116 - 0.906 μm.</td>
<td>Tool Steel</td>
<td>( R = 2.723 \times Ra^{0.5} - 0.68 )</td>
<td>0.007</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Brass</td>
<td>( R = 1.093 \times Ra + 0.6461 )</td>
<td>0.0534</td>
<td>0.901</td>
</tr>
<tr>
<td></td>
<td>Copper</td>
<td>( R = 0.861 \times Ra + 0.9815 )</td>
<td>0.0098</td>
<td>0.977</td>
</tr>
</tbody>
</table>
Table 5.2 Repeatability of the Optical parameter (SD/RMS) measurement results

<table>
<thead>
<tr>
<th>Reading number</th>
<th>11 Tool steel specimens calibrated mechanically in Ra microns (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>0.12 0.20 0.23 0.25 0.46 0.51 0.56 0.66 0.76 0.89</td>
</tr>
<tr>
<td>1</td>
<td>0.31 0.33 0.30 0.50 0.58 1.21 1.14 1.45 1.27 1.52 1.82</td>
</tr>
<tr>
<td>2</td>
<td>0.32 0.36 0.50 0.48 0.62 1.16 1.21 1.44 1.33 1.71 1.87</td>
</tr>
<tr>
<td>3</td>
<td>0.42 0.42 0.50 0.44 0.58 0.96 1.18 1.86 1.36 1.52 1.51</td>
</tr>
<tr>
<td>4</td>
<td>0.26 0.50 0.35 0.40 0.69 1.09 0.99 1.06 1.44 1.67 1.52</td>
</tr>
<tr>
<td>5</td>
<td>0.35 0.28 0.45 0.45 0.76 1.07 1.11 1.37 1.42 1.64 1.71</td>
</tr>
<tr>
<td>6</td>
<td>0.39 0.35 0.38 0.43 0.68 1.14 1.12 1.26 1.62 1.47 1.69</td>
</tr>
<tr>
<td>7</td>
<td>0.27 0.35 0.46 0.43 0.64 1.06 1.18 1.04 1.58 1.67 1.64</td>
</tr>
<tr>
<td>8</td>
<td>0.29 0.21 0.52 0.52 0.92 0.92 1.13 1.37 1.65 1.75 1.63</td>
</tr>
<tr>
<td>9</td>
<td>0.22 0.39 0.38 0.45 0.68 1.50 1.30 1.60 1.76 1.63</td>
</tr>
<tr>
<td>10</td>
<td>0.23 0.41 0.33 0.48 0.56 0.82 1.07 1.43 1.63 1.40 1.75</td>
</tr>
</tbody>
</table>

| Mean         | 0.31 0.36 0.42 0.46 0.67 1.03 1.14 1.29 1.49 1.61 1.67         |
| STD          | 0.06 0.07 0.07 0.04 0.10 0.12 0.08 0.14 0.13 0.12 0.11         |
| Max          | 0.42 0.50 0.52 0.52 0.92 1.21 1.30 1.45 1.65 1.76 1.87         |
| Min          | 0.22 0.21 0.30 0.40 0.56 0.82 0.99 1.03 1.27 1.40 1.51         |
| Range        | 0.20 0.29 0.22 0.12 0.36 0.39 0.31 0.42 0.38 0.36 0.36         |

Coefficient of variation

| 19  | 19  | 16  | 8.7 | 15  | 11.6 | 7   | 10.8 | 8.7  | 7.4  | 6.6  |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Table 5.3 Repeatability of the stylus measurement results

<table>
<thead>
<tr>
<th>Reading number</th>
<th>11 Tool steel specimens calibrated mechanically in Ra microns (μm)</th>
<th>0.10</th>
<th>0.12</th>
<th>0.20</th>
<th>0.23</th>
<th>0.25</th>
<th>0.46</th>
<th>0.51</th>
<th>0.56</th>
<th>0.66</th>
<th>0.76</th>
<th>0.89</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0.13</td>
<td>0.10</td>
<td>0.18</td>
<td>0.22</td>
<td>0.24</td>
<td>0.47</td>
<td>0.51</td>
<td>0.62</td>
<td>0.61</td>
<td>0.76</td>
<td>0.81</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.11</td>
<td>0.12</td>
<td>0.20</td>
<td>0.23</td>
<td>0.25</td>
<td>0.43</td>
<td>0.48</td>
<td>0.61</td>
<td>0.66</td>
<td>0.81</td>
<td>0.89</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.13</td>
<td>0.11</td>
<td>0.17</td>
<td>0.23</td>
<td>0.25</td>
<td>0.38</td>
<td>0.56</td>
<td>0.66</td>
<td>0.76</td>
<td>0.71</td>
<td>0.96</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.14</td>
<td>0.11</td>
<td>0.18</td>
<td>0.23</td>
<td>0.25</td>
<td>0.48</td>
<td>0.48</td>
<td>0.53</td>
<td>0.66</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.11</td>
<td>0.13</td>
<td>0.14</td>
<td>0.24</td>
<td>0.25</td>
<td>0.38</td>
<td>0.41</td>
<td>0.58</td>
<td>0.79</td>
<td>0.76</td>
<td>0.39</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0.11</td>
<td>0.12</td>
<td>0.18</td>
<td>0.20</td>
<td>0.25</td>
<td>0.48</td>
<td>0.69</td>
<td>0.56</td>
<td>0.51</td>
<td>0.66</td>
<td>0.94</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>0.11</td>
<td>0.11</td>
<td>0.19</td>
<td>0.22</td>
<td>0.27</td>
<td>0.51</td>
<td>0.51</td>
<td>0.58</td>
<td>0.69</td>
<td>0.81</td>
<td>0.89</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>0.11</td>
<td>0.12</td>
<td>0.18</td>
<td>0.20</td>
<td>0.25</td>
<td>0.43</td>
<td>0.43</td>
<td>0.43</td>
<td>0.71</td>
<td>0.84</td>
<td>0.96</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>0.11</td>
<td>0.11</td>
<td>0.18</td>
<td>0.22</td>
<td>0.25</td>
<td>0.51</td>
<td>0.56</td>
<td>0.56</td>
<td>0.68</td>
<td>0.76</td>
<td>0.89</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>0.12</td>
<td>0.12</td>
<td>0.17</td>
<td>0.25</td>
<td>0.25</td>
<td>0.46</td>
<td>0.51</td>
<td>0.51</td>
<td>0.56</td>
<td>0.77</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Mean | 0.12 0.12 0.18 0.22 0.25 0.45 0.51 0.59 0.66 0.77 0.91
STD  | .009 .007 .014 .015 .006 .046 .077 .062 .086 .078 .046

Coefficient of variation

| 8.4   6.3  8.1  7.0  2.6  10.3  15  10.6  12.9  10  5.1 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Table 5.4: Ra values of a ground toolsteel surface from a mitutoyo surftest III profilometer.

<table>
<thead>
<tr>
<th>Reading</th>
<th>Ra (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.50</td>
</tr>
<tr>
<td>2</td>
<td>0.48</td>
</tr>
<tr>
<td>3</td>
<td>0.55</td>
</tr>
<tr>
<td>4</td>
<td>0.43</td>
</tr>
<tr>
<td>5</td>
<td>0.50</td>
</tr>
<tr>
<td>6</td>
<td>0.48</td>
</tr>
<tr>
<td>7</td>
<td>0.55</td>
</tr>
<tr>
<td>8</td>
<td>0.50</td>
</tr>
<tr>
<td>9</td>
<td>0.68</td>
</tr>
<tr>
<td>10</td>
<td>0.40</td>
</tr>
<tr>
<td>Mean</td>
<td>0.505</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.076</td>
</tr>
<tr>
<td>Maximum value</td>
<td>0.68</td>
</tr>
<tr>
<td>Minimum value</td>
<td>0.40</td>
</tr>
<tr>
<td>Range</td>
<td>0.28</td>
</tr>
<tr>
<td>Precision expressed in STD/Mean</td>
<td>15%</td>
</tr>
</tbody>
</table>
Table 5.5: Values of $Ra$ of the same ground surface (as Table 5.4) from the optical system

<table>
<thead>
<tr>
<th>Reading</th>
<th>Optical reading</th>
<th>Converted to $Ra$ ($\mu m$) by eq. 5.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.14</td>
<td>0.52</td>
</tr>
<tr>
<td>2</td>
<td>1.21</td>
<td>0.56</td>
</tr>
<tr>
<td>3</td>
<td>1.18</td>
<td>0.54</td>
</tr>
<tr>
<td>4</td>
<td>1.05</td>
<td>0.47</td>
</tr>
<tr>
<td>5</td>
<td>1.11</td>
<td>0.503</td>
</tr>
<tr>
<td>6</td>
<td>1.12</td>
<td>0.503</td>
</tr>
<tr>
<td>7</td>
<td>1.18</td>
<td>0.54</td>
</tr>
<tr>
<td>8</td>
<td>1.13</td>
<td>0.504</td>
</tr>
<tr>
<td>9</td>
<td>1.25</td>
<td>0.58</td>
</tr>
<tr>
<td>10</td>
<td>1.07</td>
<td>0.48</td>
</tr>
<tr>
<td>Mean</td>
<td>1.14</td>
<td>0.52</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.062</td>
<td>0.035</td>
</tr>
<tr>
<td>Maximum value</td>
<td>1.25</td>
<td>0.58</td>
</tr>
<tr>
<td>Minimum value</td>
<td>1.05</td>
<td>0.47</td>
</tr>
<tr>
<td>Range</td>
<td>0.20</td>
<td>0.11</td>
</tr>
<tr>
<td>Precision expressed in STD/Mean</td>
<td>5.4%</td>
<td>6.7%</td>
</tr>
</tbody>
</table>
5.2. Spectral Analysis

Two methods of frequency spectrum characterization, the RMS and the maximum peak are used in this study to quantify roughness. A bandwidth of 5 to 50 mm$^{-1}$ was used, since most of the useful information is contained in this range. To detect the trend of the data, both the maximum peak and the RMS value were plotted against the surface roughness Ra as obtained from a mechanical stylus device for a number of tool steel specimens of different roughness. The resulting correlation curves shown in Figures 5.5 and 5.6 indicate that there is a relationship between either of these two parameters and Ra for illumination configuration 1. As can be seen, the two correlation curves are similar.

A least-square fit was used to define the equation for the correlation curves. For the roughness Ra between 0.1 - 1.1 μm, an exponential function was found to give the best fit. However, for a smaller roughness range, eg. Ra between 0.1 - 0.66 μm, a linear function was more appropriate, see Table 5.6 for the fitted equations and the corresponding correlation coefficients. The correlation curves as established, provide a means to relate the parameters of the frequency spectrum to the surface roughness Ra.

The correlation procedures were then repeated for configuration 2, however no correlation was found as shown in Figures 5.7 and 5.8.
Figure 5.5 Relation between spectrum RMS and ground surface roughness for tool steel specimens under configuration 1.
Figure 5.6 Relation between spectrum maximum peak and ground surface roughness for tool steel specimens under configuration 1.
Figure 5.7 Relation between spectrum RMS and ground surface roughness for tool steel specimens for configuration 1.
Figure 5.8 Relation between spectrum maximum peak and ground surface roughness for tool steel specimens for configuration 2.
Table 5.6 Correlation of optical roughness parameter and Ra

<table>
<thead>
<tr>
<th>Roughness Range (Ra)</th>
<th>Parameter</th>
<th>Correlation Equation</th>
<th>Coefficient of Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 - 1.1 μm.</td>
<td>RMS</td>
<td>( R = 0.334 \cdot Ra^{0.489} )</td>
<td>0.976</td>
</tr>
<tr>
<td></td>
<td>Peak</td>
<td>( R = 1.172 \cdot Ra^{0.459} )</td>
<td>0.974</td>
</tr>
<tr>
<td>0.1 - 0.6 μm.</td>
<td>RMS</td>
<td>( R = 0.335 \cdot Ra + 0.800 )</td>
<td>0.981</td>
</tr>
<tr>
<td></td>
<td>Peak</td>
<td>( R = 1.067 \cdot Ra + 0.327 )</td>
<td>0.968</td>
</tr>
</tbody>
</table>
5.3. Measurement in Oil

To simulate the surface roughness measurement process in a production environment, this work was extended to the case where the specimen surface is immersed in oil. In this setup, the specimen was illuminated by a fiber optic bundle under configuration 1. The output end of the fiber optic and the specimen are immersed in oil. This is to eliminate any unwanted reflection from the oil surface. The grazing angle was kept at 5 degrees. Roughness measurement was then carried out on tool steel specimens and the results were correlated to the average surface roughness Ra as shown in Figure 5.9. A linear curve can be fitted to the data in the Ra range of 0.1 to 0.7µm. The slope of the curve however, is small in comparison with similar measurements made in oil-free condition, thus the sensitivity of the measurement is reduced, see Figure 5.10.
Figure 5.9 Relation between optical parameter and ground surface roughness for tool steel specimens immersed in oil.
Figure 5.10 Correlation curves for oil-free and oil-immersion conditions.
5.4. Surface Flaw Detection

Surface flaws are irregularities that do not appear in a consistent pattern, and they are not desirable since they degrade the quality of a surface which in turn affects the functional behavior and performance of the workpiece. Therefore, it is necessary to discriminate flaws in an on-line inspection process.

Traditional ways of flaw detection in a vision system are thresholding and template matching [28].

5.4.1. Thresholding

The thresholding technique normally requires a knowledge of the histogram of an image. Calculations are then performed on the histogram to obtain an optimum threshold value to discriminate the interested part from the others. For flaws that do not have great contrast difference from the background, it is difficult to select an optimum threshold level. Thresholding at too high a level results in a loss of information, while thresholding at too low a level gives rise to undesirable background clutter.

To illustrate this, let's consider a picture of a surface containing flaws shown in Figure 5.11. The thresholded image shown in Figure 5.12 indicates that the flaw cannot be successfully separated from the background. This is due to the fact that the contrast difference is small.
5.4.2. Template Matching

Template matching involves the convolution of a template array to an image array. Different template arrays are used to detect different regional properties. The arrays frequently used are matrices of 3 by 3. Figures 5.13 shows various types of template arrays that are used to detect edges at different directions. Let $W_1, W_2, \ldots, W_9$ represent the coefficients in a 3 X 3 template, and let $X_{11}, X_{12}, \ldots, X_{33}$ be the grey levels of the pixels in an image array as shown in Figure 5.14. When the template moves around the pixel point $X_{22}$, the resulting product is defined as:

$$P = W_1X_{11} + W_2X_{12} + \ldots + W_9X_{33}$$

This calculated value is then compared to a predetermined threshold value $T$. If the result is greater than the threshold value, then an edge exists and vice versa.

Figure 5.15 shows the resulting image when a horizontal edge detection array is multiplied by the image array in Figure 5.11. As can be seen, this edge detection array does not eliminate all the background clutter, this may be due to the incorrect selection of the threshold value. Thus, before using this method, a trial and error approach has to be performed to derive an optimum threshold value. In this study, a new technique for flaw detection is investigated.

5.4.3. Proposed Technique

Surface flaws and surface roughness are two different phenomena. Surface flaws are irregularities which change the light
scattering pattern of a machined surface. The scattering patterns of a normal surface and that of a damaged surface are shown in Figures 5.16(a) and 5.16(b). It can be seen that for a normal machined surface, the distribution is uni-modal and skewed slightly to the right (skewness is positive). In addition, the kurtosis of the distribution is slightly more than 3. The skew is a third order normalized central moment which measures the symmetry of the distribution and is defined as follows:

\[ \alpha_3 = \frac{\sum_{i=0}^{255} F_i \times (X_i - \bar{X})^3}{SD^3 \times N} \] ........................(5.3)

The kurtosis is a fourth order normalized central moment which measures the peakedness of the distribution and is defined as follows:

\[ \alpha_4 = \frac{\sum_{i=0}^{255} F_i \times (X_i - \bar{X})^4}{SD^4 \times N} \] ........................(5.4)

where \( N, SD, F_i \) and \( X_i \) are defined in section 4.1.

For a damaged surface, the distribution is now a combination of two populations, one belongs to the flaws, and the other, the surface. The population which belongs to the flaws has a lower mean and a much lower spread. Thus, the addition of this population to that of the regular surface causes a shifting of the distribution from uni-modal to bi-modal with the second peak at the left side of the distribution. The form of this peak depends on the size, the amount and the severity of the flaws. Furthermore, the addition of the flaw population to the original distribution reduces the kurtosis value and causes the skewness...
of the histogram to decrease from a slightly positive value to a negative value. By utilizing these properties, one can check the presence of surface flaws by simply detecting the sign of the skewness of the distribution and/or examining the kurtosis value. To illustrate this technique, let's consider the following examples.

Figure 5.17 shows a picture of a ground surface. The skew and kurtosis of the distribution are found to be 0.31 and 3.16 respectively which characterize a good quality surface.

Figure 5.18 shows a picture of a surface contains a flaw. The skew and kurtosis of the distribution are found to be -0.29 and 3.36 respectively.

Figure 5.19 shows a picture of a surface containing a larger size flaw as compared to the previous one. The flaw can be easily detected from the bimodal shape of the histogram distribution. The skew and kurtosis of the distribution are found to be -0.28 and 2.62.

Figure 5.20 shows a picture of a surface which contains small flaws which are evenly distributed. The histogram distribution does not show any bimodal shape, The skew of the distribution is found to be 0.28 and the kurtosis value is found to be 2.62.

The results obtained from the above measurements were inconsistent. No definite trends can be established to relate the skew and the kurtosis of a distribution to detect surface flaws.
Figure 5.11 An original image of a machined surface contains flaws.

Figure 5.12 The threshold image
<table>
<thead>
<tr>
<th>North</th>
<th>Northeast</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>-2</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>East</th>
<th>Southeast</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>-1</td>
<td>-2</td>
</tr>
<tr>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>South</th>
<th>Southwest</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>1</td>
<td>-2</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>West</th>
<th>Northwest</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>-2</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 5.13 Template matching arrays.
Figure 5.14 Calculations procedure of template matching.
Figure 5.15 The resulting image after a horizontal edge detection is performed on the original image.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 5.16(a) Histogram distribution for a normal surface.

Figure 5.16(b) Histogram distribution for a damaged surface.
Figure 5.17(a) A photograph of a normal ground surface.

Figure 5.17(b) The histogram of the image shown in 5.17(a) (skew=0.31 kurtosis=3.16).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 5.18(a) A photograph of a surface contains a medium size flaw.

Figure 5.18(b) Histogram of the picture shown in 5.18(a) (skew=-0.29 kurtosis=3.36).
Figure 5.19(a) A photograph of a surface contains a large size flaw.

Figure 5.19(b) Histogram of the picture as shown in 5.19(a) (skew=-0.28 kurtosis=2.16).
Figure 5.20(a) A photograph of a surface containing distributed flaws.

Figure 5.20(b) Histogram of the picture as shown in 5.20(a) (skew=0.28 kurtosis=2.62).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
CHAPTER VI

CONCLUSIONS

A new optical system for surface roughness assessment has been developed. This system comprises an incandescent white light source, a CCD camera, an imaging system and a micro-computer system. Two measurement procedures were developed to analyse the light scattering pattern of a surface for various light incident directions. From the results of these measurements, optical parameters were derived to quantify the machined surface roughness $R_a$. In general, the new measurement technique offers a fast and convenient way for surface roughness assessment.

The optical parameters were correlated with the mechanical roughness $R_a$ as obtained from a stylus instrument. Good correlations were found. The precision of the optical technique was proven to be much better than that from the traditional stylus instrument.

Roughness measurements were carried out for different materials and unique relationships were established.

The study was also extended to the case where surfaces were immersed in oil and reasonable correlation was found.

Based on the results of this investigation the following conclusions are made:

86
1. It is possible to use a white light source in conjunction with a micro-computer based vision system to measure surface roughness over a broad range. For the histogram analysis, the optical parameter SD/RMS (standard deviation over the RMS height of the distribution) can be effectively used to characterize the machined surface roughness Ra of a "ground" surface.

For the spectral analysis, the maximum peak and spectrum RMS level were used. The measurement results for various illumination configurations are summarized as follows:

Configuration 1: **Light perpendicular to the lay direction**

a) Histogram analysis

The relationship between the optical parameter SD/RMS to the stylus calibrated surface roughness can be expressed by a power function in the roughness range Ra = 0.1 to 1 µm for tool steel specimens and by a linear function for brass and copper specimens in the same range.

The correlation equations are shown as follows:

- **Tool steel**  
  \[ R = 2.72 \times R_a^{0.5} - 0.68 \]

- **Brass**  
  \[ R = 1.09 \times R_a + 0.65 \]

- **Copper**  
  \[ R = 0.86 \times R_a + 0.98 \]

where \( R \) = optical number SD/RMS

\( R_a \) = machined surface roughness Ra as measured by a stylus devices in microns.
b) Spectral analysis

The relationship between the Spectrum RMS and Maximum Peak to the stylus calibrated surface roughness can be expressed by a power function in the roughness range of 0.1 to 1.1µm for tool steel specimens.

The correlation equations are as follows:

\[ R = 1.17 \times Ra^{0.46} \]  for Max. Peak

and

\[ R = 0.33 \times Ra^{0.90} \]  for Spectrum RMS

For a smaller roughness range (Ra = 0.1 to 0.6µm), a linear equation is more appropriate.

For Max. Peak \[ R = 1.07 \times Ra + 0.33 \]

Spectrum RMS \[ R = 0.34 \times Ra + 0.80 \]

Configuration 2: Light and camera normal to the surface

a) Histogram analysis

A inverse linear correlation was found between the optical parameter (SD/RMS) and machined surface roughness Ra in the roughness range of 0.1 to 0.7µm. The correlation equation was found to be:

\[ R = -1.18 \times Ra + 1.21 \]

b) Spectral analysis

No correlation was found.

Configuration 3: Light parallel to the lay direction

Due to very low intensity contrast differences between smooth and rough surfaces, no correlation was found.
2. For Configuration 1, (light perpendicular to the lay direction), the highest measurement sensitivity was obtained when the light source was located at a grazing angle of 5 degrees and 10 cm. away from the surface.

The measurement sensitivity and the useful range of optical surface roughness measurement decreases as the grazing angle increases. This condition holds for the materials used in the study, namely ground tool steel, copper and brass.

3. The study was extended to the case where measurements were made under oil. Among those three configurations, correlation was found in the roughness range of 0.1 to 0.7µm for light perpendicular to the lay direction (configuration 1). No observable trends could be established for the other two configurations.

4. The precision of the measurement of this system is much better than that of the stylus instrument. For the optical system, the precision was found to be 6.7% compared to 15% for the stylus instrument (see table 5.4 and 5.5). Both measuring devices have the same degree of repeatability.

5. An attempt was made to quantify surface flaws by the skew and kurtosis of a greylevel histogram distribution. Due to the inconsistency of the analysis results, no conclusive relations could be established.
CHAPTER VII
RECOMMENDATIONS

It is recommended that future work should be concentrated in the following areas:

1. The scattering patterns of surfaces machined by different processes such as milling and turning needs to be investigated so as to establish calibration curves for the system.

2. In the case of surface flaws, more work is needed to derive a better parameter to characterize the surface conditions.

3. Measurement of roughness in the lay direction is limited to Ra in the range of 0.1 to 0.6μm. More study is needed to improve the range of measurement.

4. It has also been shown that the system sensitivity is reduced in oil. This may due to the influence of unwanted reflection from the oil surface. Therefore, a more dedicated optical setup is needed for further investigation.

5. Other surface patterns such as angular, multi-directional, circular and radial should also be investigated in the future.
6. The analysis techniques used were based on the assumption that the light source intensity was constant throughout the measurement. However, in real situation, the illumination intensity fluctuates as the supply voltage changes. Therefore a better means to regulate the voltage is needed to maintain a constant illumination.

7. Further study can be conducted to correlate the optical system to other roughness parameters such as Rq, Rt, Rz etc.
REFERENCE


APPENDIX I.

Equipment Descriptions
PRODUCT CATALOG

CCD PLUS

TM-34K/TM-36K SERIES
SOLID STATE CAMERAS AND
ACCESSORIES

PULNIX
The MATROX PIP-512 is a full-feature image digitization and display module for your IBM PC, AT, XT or plug-compatible computer. This card has all the high-performance features characteristic of top-of-the-line image processing systems such as real-time 8-bit digitization, a 512 x 512 video buffer, multiple input and output lookup tables, a write-protect mask, and color display.

Equally important, the PIP-512 integrates easily into a PC system. It occupies only one expansion slot and consumes a mere 15 Watts of power. Diagnostic support is built into the hardware. As a result, the diagnostic program, PIP-TEST, is capable of detecting over 95% of all possible problems.

PIP-EZ, a software package conceived to help the programmer to develop an application, is supplied free of charge. PIP-EZ consists of an installable device driver under PC-DOS and applications libraries for all major DOS language (BASIC, PASCAL, FORTRAN, and C).
### PIP-512 FEATURES

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Speed A/D Converter</td>
<td>A flash A/D converter digitizes RS-170/330 signals in real-time (1/30 sec) to 256 discrete intensity levels.</td>
</tr>
<tr>
<td>Sync Control</td>
<td>Both an internal crystal generated sync and PLL genlock to an external signal are supported.</td>
</tr>
<tr>
<td>Display Resolution</td>
<td>512 × 512 pixels</td>
</tr>
<tr>
<td>Bits/pixel</td>
<td>8</td>
</tr>
<tr>
<td>Refresh Rate</td>
<td>50Hz or 60Hz interlaced</td>
</tr>
<tr>
<td>Image Buffer Capacity</td>
<td>PIP-512: 512 × 512 PIP-1024: one 1024 × 1024 frame or four 512 × 512 frames</td>
</tr>
<tr>
<td>Input Lookup Tables</td>
<td>Eight independently-selectable lookup table maps.</td>
</tr>
<tr>
<td>Color Output</td>
<td>Three lookup tables and three D/A converters allow for the display of 256 colors or shades of grey from a palette of 16.7 million colors.</td>
</tr>
<tr>
<td>Transparent Memory Access</td>
<td>The Video RAM can be accessed at all times without causing interference on the screen.</td>
</tr>
<tr>
<td>Write Protect Mask</td>
<td>Individual planes can be protected from overwriting. Protected planes can be used for graphics, and text.</td>
</tr>
<tr>
<td>Pan &amp; Scroll</td>
<td>The PIP-512 provides programmable roam capabilities to a resolution of 8 pixels horizontally and 16 lines vertically.</td>
</tr>
<tr>
<td>DMA Capability</td>
<td>Any DMA channel can be used to copy data to and from main memory. An interrupt on completion allows the CPU to continue with other work during the transfer.</td>
</tr>
<tr>
<td>I/O Interface</td>
<td>Sixteen I/O registers are used to control each PIP-512. Only one location is taken up in the 10-bit I/O map used by older controllers to ease integration.</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>Extensive use of CMOS technology keeps the power consumption down to a mere 15 Watts.</td>
</tr>
<tr>
<td>Applications Software</td>
<td>PIP-EZ, a driver package compatible with PC-DOS (versions 2.0 and above) and all major languages (BASIC, C, PASCAL and FORTRAN) aids the user to bring up an application quickly and painlessly.</td>
</tr>
<tr>
<td>Diagnostics</td>
<td>A sophisticated diagnostic program aided by hardware support detects more than 95% of all possible faults without the use of either a camera or a monitor.</td>
</tr>
</tbody>
</table>
The PIP-512 is a single board controller that adds real-time image acquisition and display capabilities to an IBM PC. An imaging sub-system will enhance the PC allowing it to be used in many new applications such as robotic vision, medical display, image archival and the industrial arts.

The PIP-512 can be thought of as a memory buffer containing a digital representation of an image. The image is broken down into 262,144 individual points (known as pixels), arranged in a 512 x 512 matrix. Each pixel is contained in a single byte and hence represents the intensity of light at that point to one of 256 discrete intensity levels. Three interfaces exist to the buffer: a PC-bus interface allowing CPU or DMA access; an analog input allowing an image to be grabbed from a camera; and an analog output allowing the image to be displayed on a monitor. A sophisticated timing circuit allows all three interfaces to be used at the same time without any restrictions.

**PC-bus Interface** — This sub-system allows the CPU or DMA unit to access the buffer. X-Y coordinate addressing is used, meaning that the CPU accesses an individual pixel by referring to its relative position in the image. Both random and sequential access are supported, the latter using an autoincrement feature which automatically increments the X-Y registers after each access. Using this feature, the DMA unit can be used to transfer part or all of the image to or from the PC’s memory. An optional interrupt is supplied on completion of the DMA transfer, allowing the CPU to continue with other work while the transfer is taking place.

**Analog Input** — This interface is used to convert an analog signal to digital format and place it in the frame buffer in real-time (1/30th sec). Both single shot and continuous grab are supported. As the signal is being digitized, it is passed through software-controlled setup and gain controls and a 256 entry look-up table. These are used for correcting line losses and image pre-processing. A write-protect mask can be used to selectively prevent overwriting of any of the 8 bit planes. Protected planes can be used to store graphics, characters, or cursors. The write-protect mask can also be used at the CPU interface.

**Analog Output** — The image is displayed by converting the digital intensity value for each pixel back into an analog signal. The 8 bit pixel index is passed through a color look-up table which maps the 256 possible intensity values to 256 colors or shades of grey. The 256 display colors are selectable from a 16.7 million color palette. A keying circuit allows the user to overlay the contents of the frame buffer with the incoming signal.
FRAME GRABBER
The PIP-512 can digitize pictures in real-time (1/60 sec/field) from the Frame Grab input port. This port accepts RS-170 or RS-330 type composite analog video signals from an external video source, such as a camera or another video board. Both the 60Hz/525 line and 50Hz/625 line international scanning standards are supported.

Multiple inputs — Four separate inputs are supported, three external and one internal loop-back. Digitization of the external video signal can be done in continuous mode (live video update) or in snapshot mode (a single still frame).

The PIP-512 can genlock to an externally generated sync signal or it can provide an internally generated, crystal controlled, sync. When an external composite video signal is supplied, a sync separator circuit extracts the relevant timing information and uses a precision phase-locked loop (PLL) comparator to provide drift-free genlock.

Setup and Gain Controls — Programmable setup and gain controls are provided to clamp the black level of the analog video input signal to a known reference value prior to A/D conversion, and to restore the voltage level of this signal to a full 1V peak-to-peak (an input range of 0.4 to 2.0 volts can be accommodated by the amplifier). Both gain and offset are selectable in 256 increments.

Input Lookup Tables — A high speed 2K x 8 RAM input look-up table is included for pre-processing of raw video data. The input LUT maps the 8-bit value on the video input bus (from the A/D or from an external buffer) into a new 8-bit value which is written into memory. Eight separate lookup tables can be mapped at one time. The input lookup table can be used to stretch the contrast of an image in which most of the information is concentrated in a narrow range of intensity values.

PC-BUS IMAGE ACCESS
The PIP-512 is accessed from the PC bus using I/O-mapped XY coordinate registers. Both random and sequential accesses are supported. An auto-increment mode is supported whereby the XY registers are automatically incremented after access. This speeds up sequential access to an average access rate of 800nsec per pixel.

DMA Access — In this mode, the DMA unit may be used to copy all or part of the image to/from the PC’s memory. Optional interrupt on completion is supported when DMA access is being used. This allows the CPU to continue with other work while the transfer is taking place. An entire image can be copied from the PC’s memory to the frame buffer in just a third of a second using the DMA interface.

Transparent Memory — The PIP-512’s video memory features a transparent arbitration circuit which allows images to be updated at any time (not just during blanking) without causing interference on the display.

IMAGE STORAGE
The PIP-512 contains 256K bytes of video RAM memory organized as 8 planes of 512 x 512 pixels. In 525 line/60Hz systems, 512 points horizontal by 480 lines vertical are visible. In 625 line/50Hz systems, all 262,144 pixels are displayed. A crystal with a frequency of 10MHz is used to clock data transfers from the input and to the output, providing real-time (1/30th sec) transfers in both directions.
Write Protect Mask - A write-protect mask can be used to enable or disable write access to any of the 8 individual memory planes. By using this register, specific planes can be allocated to graphics, text, or cursor overlays; and will not be disturbed when new images are loaded.

Pan & Scroll — The PIP-512 has pixel pan (horizontal slew) and scroll (vertical slice) capabilities with a resolution of 8 pixels and 16 lines respectively. The relative position of the display origin (upper left hand corner of the screen) can be positioned anywhere within the video memory.

VIDEO OUTPUT SECTION

Video Output Look-up Table — The 8 bit/pixel intensity data stored in the video memory indexes an output look-up table (LUT) prior to display. The output LUT, which consists of three 2K x 8 segments of high-speed RAM and three precision 8-bit D/A converters, allows the user to map the 256 possible intensity values of each of the stored pixels to any 256 colors or shades of grey. The 256 colors stored in the output LUT are selectable from an available palette of over 16 million shades. The output LUT provides for simple grey scale displays, pseudo-color enhanced displays, graphics and alphanumeric overlays, and special effects such as contouring.

The look-up table RAMs contain 2K entries for each R, G, and B channel. This means that 8 separate LUT maps (256 entries in each map) can be stored simultaneously. Switching from one map to another is software programmable and is controlled via a map select register. Multiple map storage means that several different image enhancement algorithms can be invoked with simple commands from the user's host without reloading the entire LUT.

Video Keyer - A video keying circuit in the PIP-512 allows the user to mix the incoming video signal with the contents of the video RAM buffer. The least significant bit of each pixel in the video RAM is used to select between the RAM buffer and the input. If this bit is set then the contents of the memory will be displayed; otherwise the incoming signal is displayed. Using the keyer, 128 intensities can be displayed together with 128 distinct overlay colors.

Note that both the keyer and the write mask may be used to save overlays. The keyer has the advantage of giving 128 image intensities and 128 overlay colors at the same time. The write mask, in contrast, prevents the overlay from being destroyed while an image is being acquired. The choice of method will depend on the application.
The PIP-512 software library, PIP-EZ, is designed to ease the task of creating an application, not to be an application. PIP-EZ is designed to eliminate the need to interface directly with the hardware. Instead the applications programmer works with standard system calls, a well-defined library interface and a high-level language.

Functionally, PIP-EZ provides the applications programmer with interfaces at three levels — an applications library and language binding, a DOS block device driver (version 2.0 and above), and a BIOS driver. The user may freely mix use of all three interfaces. Thus the applications library might be used to configure the board while the BIOS is used for high speed transfers to and from the frame buffer.

**BIOS Driver** — The lowest level interface supported is at the BIOS level. The BIOS uses one software interrupt (which is user configurable). Sixteen functions provide high speed access. This interface is only available from assembler as it is expected that any application needing extra speed would be written in assembler. It is possible, however, to write a simple language binding to access this interface from a high level language. Some of the applications library routines use the BIOS for faster execution.

**DOS Driver** — The DOS Driver makes the PIP-512 look like a standard block device (e.g. a disk drive) with one file on the device (four files when using the PIP-1024). Each file represents one frame buffer. Thus to access the frame buffer, the standard open, close, read, write, and seek calls of a high level language may be used. The IOCTL system calls are used for specialized imaging functions such as LUT management and frame grabbing.

---

**PIE-EZ APPLICATIONS LIBRARY SUBROUTINE SUMMARY**

<table>
<thead>
<tr>
<th>Routine</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>convolv</td>
<td>general convolution around an N x M kernel</td>
</tr>
<tr>
<td>hipass</td>
<td>high pass filter using 3 x 3 kernel</td>
</tr>
<tr>
<td>bpass</td>
<td>low pass filter using 3 x 3 kernel</td>
</tr>
<tr>
<td>vdet</td>
<td>vertical edge detect using 3 x 3 kernel</td>
</tr>
<tr>
<td>hdet</td>
<td>horizontal edge detect using 3 x 3 kernel</td>
</tr>
<tr>
<td>lapdet</td>
<td>Laplacian edge detect using 3 x 3 kernel</td>
</tr>
<tr>
<td>bdet</td>
<td>Bi-Laplacian edge detect using 3 x 3 kernel</td>
</tr>
<tr>
<td>window</td>
<td>set window for histograms and convolutions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Routine</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>index</td>
<td>specify current drawing index</td>
</tr>
<tr>
<td>moveo</td>
<td>set current pen position</td>
</tr>
<tr>
<td>lineo</td>
<td>draw a line</td>
</tr>
<tr>
<td>rect</td>
<td>draw a rectangle</td>
</tr>
<tr>
<td>rectf</td>
<td>draw a filled rectangle</td>
</tr>
<tr>
<td>clear</td>
<td>set entire frame buffer to one color</td>
</tr>
<tr>
<td>grid</td>
<td>draw a grid with variable sized squares</td>
</tr>
<tr>
<td>text</td>
<td>write character string of variable size</td>
</tr>
<tr>
<td>font</td>
<td>select character font for text commands</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Routine</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>histo</td>
<td>generate a histogram</td>
</tr>
<tr>
<td>cont</td>
<td>lookup table contouring</td>
</tr>
<tr>
<td>thresh</td>
<td>lookup table thresholding</td>
</tr>
</tbody>
</table>
Since the PIP-512 looks to DOS like a normal disk drive, standard DOS utilities will work on the frame buffer. For example,

\texttt{copy A: image D: image.1}

will transfer a saved image from a diskette file to the frame buffer. Other useful commands include rename, delete, dir and I/O redirection.

\textbf{Language Bindings} — Since DOS only supports access from assembler, language bindings are supplied for major high-level languages — Pascal, Fortran, C (large and small models) and BASIC (interpreted and compiled). The read, write, open, close and seek calls of the language are used to access the frame buffer. Since none of these languages support the IOCTL system calls directly, twenty one subroutine calls in each language are supplied for the various IOCTL system call options. In interpreted BASIC, an assembly language load module provides the interface. For all other languages, a standard link library module is used.

\textbf{Applications Library} — Included in the link module is a series of subroutines which will help to create your applications. The library includes graphics routines (lineto, moveto, characters, rectangles, and grids), and imaging routines (convolutions, histograms and lookup table management). The imaging routines work with a user-defined window in the video RAM. This speeds up operation of the routines as only the window specified is manipulated, not the full frame buffer.

\textbf{Diagnostics} — The Diagnostics program is used to test the functionality of the board. Specialized functions are included in the hardware to aid in diagnostic testing. These functions include an internal loopback mode and an I/O address check mechanism. With the aid of these test functions, a sophisticated diagnostic program verifies that the board is functioning to 95% accuracy.
Medical
- CAT scanners
- X-ray/radiology
- Ultrasound
- Thermography
- Electron Microscopy

Scientific
- Earth Resources Planning
- Astronomy
- Oceanography
- Geology
- Seismology

Graphic Arts
- Computer Art
- Image Overlay
- Ad preparation

Inspection & Quality Control
- Tolerance Verification
- Missing Parts Spotting
- Thermography

Telecommunications
- Teleconferencing
- Image Forwarding
- Computer Mail

Security
- Automated Remote Sensing
- Access Control

Office Automation
- Image Data Bases
- Word Processing
- Documentation

Robotics
- Object Location
- Object Manipulation

Forensics
- Fingerprint Analysis
- Signature Verification

A software package built on PIP-EZ would be used to enhance boundaries and reduce noise. The output lookup tables would then be used to highlight areas of interest.

Scientific — Meteorology, Oceanography, Astronomy and Earth Resources Planning can all use the PIP-512 to display images gathered from other sources, in particular, satellite photos. The ability to transfer images rapidly from disk, to display multiple images, and to highlight areas of interest are all critical features for these applications.

Teleconferencing — Voice-only links have severe defects for information transfer. The PIP-512 can be used to digitize an image which would then be transmitted over the serial link and displayed by another PIP-512. Possible types of images include: diagrams, photos, documents, and a picture of the person speaking. Since the link tends to be slow, the multiple image store capabilities of the PIP-1024 can be very useful. Note that use of a PIP-512 can thus obviate the need for a facsimile link entirely.

Security — Image digitizers can be used in several ways for security purposes. A database containing digitized pictures of personnel who are allowed access to a restricted area can be set up and is useful, particularly after hours when a guard is unlikely to know employees personally.

Remote sensing systems can use the PIP-512 to determine whether an intruder has entered into a restricted area. An image of the area is digitized as it is left empty. At regular intervals thereafter (every few seconds), another image is digitized and compared automatically to the first. If the difference between the two exceeds a pre-defined threshold, then an alarm is sounded.

Medical — The PIP-512 can be used to display images digitized from other sources such as X-rays, ultrasound, and thermal inputs. These kinds of input devices typically exhibit low contrast and considerable noise. As a consequence, the image-enhancement capabilities of the PIP-512 are very important for this sector.
Forensics — An image digitizer is a convenient entry/display device for a wide variety of forensic data such as fingerprints, photographs, and dental records. This information can be stored in a database for later retrieval. Many items, such as fingerprints, can be automatically broken down into component parts. The encoded version of the fingerprint can then be used as an index into the database, thus allowing automatic matching and retrieval techniques to be used.

Quality Control & Inspection — Image digitizers are increasingly used on assembly lines to detect flaws in products. Missing parts, tolerances out of spec, and other such problems can be detected by comparing an image of the part under inspection with that of an idealized part.

The most common comparison technique is simply to subtract one image from the other, pixel by pixel. If the differences exceed a pre-defined threshold, then the part is rejected. Normally a human “co-worker” would be informed to take corrective action.

Graphic Arts — Image digitizers are particularly useful in the preliminary stages of Art development. Rapid integration of photos, text, and graphics can be achieved. Use of the PIP-512 will encourage attempting different layouts and designs. Manual methods are time-consuming, inhibiting the creative worker. Images can be easily modified to create the effect wanted.

In-house Publishing - The PIP-512 can be a real boon to the those needing to do their own documentation. Professional-looking work can be obtained rapidly and easily. As an example, our own production engineering department is using the PIP-512 to document assembly procedures. Formerly, photos were taken of products and modified by hand to illustrate the procedure. Now, a image of the product is digitized, modified using the graphics and text overlay capabilities of PIP-EZ and printed. The process takes only a fraction of the time previously invested.
EXPANSION CAPABILITIES

A: PIP-1024

The PIP-1024 is a variant of the PIP-512 which uses 256Kbit RAM chips. This means that the frame buffer is four times as large — 1,048,576 pixels in all. This extra memory may be mapped as either a single frame buffer 1024 \( \times \) 1024 pixels in size or as four separate 512 \( \times \) 512 buffers. In the former case the user may pan and scroll throughout the entire image while in the latter case panning and scrolling affect only the active image buffer.

No matter which mode of the PIP-1024 is being used, the PC-bus interface always has access to the entire image buffer. This means that the CPU can update one image, perhaps adding a character overlay, while another is being displayed.

The PIP-1024 is particularly useful for applications requiring rapid switching between multiple images. Medical and scientific applications are particularly likely to need this capability as it is often necessary to display the same object in different ways. An example would be a medical imaging system requiring the display of thermal images and X-Rays taken of the same part of the body.

Video Bus

A video bus expansion port allows specialized applications to have high-speed direct access to the video RAM. Specialized hardware will be required to match the bus timing. However, the applications possible using this interface are endless. Among the possibilities are a high-speed image transfer unit (1/30 second per frame) and an array processor or other ALU board. Timings for this bus can be obtained on request.

Sync Bus

A sync bus expansion port is provided to combine multiple PIP-512 boards. Up to four PIP-512s can be attached in this fashion. One board, designated the master, provides timing for the others, thus allowing synchronized operation.

The most common need for this capability is color digitization. Three PIP-512s connected together over a sync bus can be used to digitize a color image, each board digitizing one of the three primary colors, red, green, or blue. The green input is connected to the master PIP-512 and the others gain their timing from this board. In this manner color input can be gained to single-frame precision.
• PIP-512 SPECIFICATIONS •

FRAME GRABBER

Resolution 512 x 512
Bits/pixel 8
Video Inputs 4 software-selectable inputs three external sources and one internal loop-back circuit
Video Supports RS-170 and RS-330
Standards 525 line 60Hz American standard or 625 line 50Hz European standard
Sync Internal crystal-controlled sync or external gen-lock sync
Setup Control 256 discrete software-selectable increments from black to midrange
Gain Control 256 discrete software-selectable increments from 0.4V to 2.0V
Input Lookup Table 8 bits in/8 bits out, 6 software selectable maps

FRAME BUFFER

Image Store PIP-512 512 x 512
PIP-1024 one 1024 x 1024 buffer or four 512 x 512 buffers

DISPLAY UNIT

D/A convertors Three 8 bit D/A convertors for RGB color output
Pan & Scroll Software roaming with a resolution of 8 pixels and 16 lines respectively
Output 8 bits in/24 bits out
Lookup Table 256 colors or intensities from a palette of 16.7 million colors 8 software-selectable maps

BUS INTERFACES

PC BUS All signals compatible with the IBM PC, XT, AT and similar computers
I/O Space The PIP-512 uses 16 locations in the PC I/O map. These are arranged so that only one address is taken up in the 10-bit map used by many early controllers
Sync Bus Provides all signals necessary for synchronizing two or more PIP-512s. Specifications may be had on request
Video Bus Provides signals for access to the grab and display sub-systems. Specifications may be had on request

CONNECTORS

Input 4 Phono Jacks (three input sources and one sync source)
Output One IBM color adapter compatible DB9 connector for RGB color and sync. Both composite sync on green and a separate sync are supported.
PC Bus one 60-pin bus-compatible connector
Sync Bus one 10-pin right-angle connector
Video Bus one 20-pin right-angle connector

VIDEO TIMING

Active Video 60Hz 50Hz
Hor Sync Freq 15.75 KHz 15.75 KHz
Hor Sync Width 4.8 sec 4.8 sec
Ver Sync Freq 60 Hz 50 Hz
Ver Sync Width 190.5 sec 190.5 sec

DIMENSIONS

Length 335.30mm
Width 106.77 mm
Height 32.70 mm

POWER CONSUMPTION

+5VDC 2.3 Amps
-5VDC 0.0 Amps
+12VDC 200m Amps
-12VDC 50m Amps
TOTAL 14.5 Watts

ENVIRONMENTAL

Temperature Operating 5°C to 46°C
Storage -40°C to 60°C
Humidity Operating 8% to 80% (NC)
Storage 5% to 100% (NC)
EMI Radiation 6Db below FCC Class A requirements when in an XT alone

ORDERING INFO

PIP-XXXX PC bus image digitizer
512 512 x 512 frame buffer
1024 1024 x 1024 frame buffer

ACCESSORIES

PC-ICABLE-10 10’ input cable
PC-OCABLE-4 4’ output cable
PC-SCABLE-X sync bus cable

2 connects 2 PIP-512s
3 connects 3 PIP-512s
4 connects 4 PIP-512s

TRACAN ELECTRONICS CORPORATION
1200 AEROWOOD DR., UNIT 3-4
MISSISSAUGA, ONT. L4W 257
TEL: 416 – 625-7752 – 621-4917
OFFICES IN TORONTO, OTTAWA, MONTREAL

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
APPENDIX II.

Chemical Composition and Mechanical Properties of Test Samples [27]
(a) Tool Steel

K.E. 672/Newhall oil hardening alloy tool steel
A.I.S.I. type 01. BS 4659 B01
Werkstoff 1.2510

Chemical Composition:
- Carbon 0.95%
- Manganese 1.20%
- Chromium 0.55%
- Tungsten 0.55%
- Vanadium 0.20%

Mechanical Property (as hardened):
- Rockwell Hardness, C scale 63/64

(b) Brass

Chemical Composition:
- Copper 61.5%
- Zinc 35.5%
- Lead 3.0%

Mechanical Properties:
- Tensile Strength, psi 58,000
- Yield Strength, psi 45,000
- Elongation, % in 2" 25
- Shear Strength, psi 34,000
- Rockwell Hardness, B Scale 78

(c) Copper

Chemical Composition:
- Copper 99.9% minimum

Mechanical Properties:
- Tensile Strength, psi 48,000
- Yield Strength, psi 44,000
- Elongation, % in 2" 16
- Shear Strength, psi 27,000
- Rockwell Hardness, F scale 87

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
APPENDIX III.

Surface Roughness Ra of the specimens
(measured by the surftest III profilometer)
(a) Tool Steel

<table>
<thead>
<tr>
<th>Sample</th>
<th>Roughness ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.10</td>
</tr>
<tr>
<td>2</td>
<td>0.12</td>
</tr>
<tr>
<td>3</td>
<td>0.20</td>
</tr>
<tr>
<td>4</td>
<td>0.23</td>
</tr>
<tr>
<td>5</td>
<td>0.25</td>
</tr>
<tr>
<td>6</td>
<td>0.46</td>
</tr>
<tr>
<td>7</td>
<td>0.51</td>
</tr>
<tr>
<td>8</td>
<td>0.56</td>
</tr>
<tr>
<td>9</td>
<td>0.66</td>
</tr>
<tr>
<td>10</td>
<td>0.76</td>
</tr>
<tr>
<td>11</td>
<td>0.89</td>
</tr>
<tr>
<td>12</td>
<td>1.04</td>
</tr>
<tr>
<td>13</td>
<td>1.14</td>
</tr>
<tr>
<td>14</td>
<td>1.31</td>
</tr>
<tr>
<td>15</td>
<td>1.46</td>
</tr>
<tr>
<td>16</td>
<td>2.06</td>
</tr>
<tr>
<td>17</td>
<td>2.15</td>
</tr>
<tr>
<td>18</td>
<td>2.92</td>
</tr>
</tbody>
</table>

(b) Brass

<table>
<thead>
<tr>
<th>Sample</th>
<th>Roughness ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.076</td>
</tr>
<tr>
<td>2</td>
<td>0.177</td>
</tr>
<tr>
<td>3</td>
<td>0.280</td>
</tr>
<tr>
<td>4</td>
<td>0.482</td>
</tr>
<tr>
<td>5</td>
<td>0.710</td>
</tr>
<tr>
<td>6</td>
<td>0.762</td>
</tr>
<tr>
<td>7</td>
<td>0.910</td>
</tr>
<tr>
<td>8</td>
<td>1.020</td>
</tr>
<tr>
<td>9</td>
<td>1.270</td>
</tr>
<tr>
<td>10</td>
<td>1.400</td>
</tr>
</tbody>
</table>
APPENDIX IV.

Flow Charts & Computer Programs
SUBROUTINE HISANG

OBTAIN MEAN, STANDARD DEVIATION, RMS HEIGHT, SKEW AND KURTOSIS OF THE HISTOGRAM DISTRIBUTION

RETURN

SUBROUTINE FFT

PERFORM FOURIER TRANSFORM USING COOLEY FFT ALGORITHM

RETURN

SUBROUTINE FFTANG

OBTAIN SPECTRUM RMS AND MAX. PEAK OF A FREQUENCY SPECTRUM

RETURN
$ INCLUDE: 'FORINTF.H'

INTEGER*2 STATE,CHANNO,STABLE,UTABLE
INTEGER*2 QUAD,VAL,MODE,RETVAL,X1,Y1,X2,Y2
INTEGER*2 X,Y,SIZE,VTYPE,OFF,RETV
INTEGER*2 BSIZE,YCOORD,NUM,THESH,INDEX
INTEGER*2 I,J,I1,J1,SAM,QUAD1,QUAD3
INTEGER*4 MAX,BUF(256)
CHARACTER DUM,BUFFER(1024)
INTEGER*2 RET
CHARACTER*20 FNAME,FILENAME
WRITE(*,5)

5 FORMAT(T15,40(('*'),/,T15'SYSTEM L-VER.1.0 10/06/1986',
* ,/T15,40('*'))
OFF=620
RETV=INIT(OFF)
WRITE(*,*)RETV
CHANNO=2
CALL CHAN(CHANNO)
MODE=1
CALL SYNC(MODE)
VTYPE=0
CALL VIDEO(VTYPE)
STATE=1
CALL QUADM(STATE)
UTABLE=7
CALL CLEAR(STABLE,UTABLE)
500 WRITE(*,30)
30 FORMAT(/,T15,'TYPE 1 TO GRAB PICTURE',
* ,/T15,'TYPE 2 TO CLEAR SCREEN',
* ,/T15,'TYPE 3 TO CHANGE QUAD',
* ,/T15,'TYPE 4 TO GENERATE DATA',
* ,/T15,'TYPE 5 FOR OFFSET',
* ,/T15,'TYPE 6 FOR GAIN',
* ,/T15,'TYPE 7 TO SUBTRACT IMAGE',
* ,/T15,'TYPE 8 TO SAVE PICTURE',
* ,/T15,'TYPE 9 TO EXIT',
* ,/T15,'INPUT = ')
READ(*,*)NUM
IF(NUM.EQ.1) THEN
  WRITE(*,40)
40 FORMAT(/,T15,'TO GRAB PICTURE',
* ,/T15,'ENTER 1 TO ENABLE',
* ,/T15,' 0 TO DISABLE',
* ,/T15,'INPUT = ')
READ(*,*)STATE
CALL CGRAB(STATE)
WRITE(*,50)
50 FORMAT(/,T15,'PRESS ANY KEY TO CONTINUE')
READ(*,'(A)')DUM
STATE=0
CALL CGRAB(STATE)
ELSEIF (NUM.EQ.2) THEN
    WRITE(*,55)
55  FORMAT(/,T15,'CLEAR SCREEN')
    STABLE=0
    UTABLE=7
    CALL CLEAR(STABLE,UTABLE)
ELSEIF (NUM.EQ.3) THEN
    WRITE(*,60)
60  FORMAT(/,T15,'CHANGE QUAD',
        /,T15,'ENTER THE DESIRE QUAD: ')
    READ(*,*)QUAD
    CALL DQUAD(QUAD)
ELSEIF (NUM.EQ.4) THEN
    WRITE(*,101)
101  FORMAT(/,T15,'GENERATE DATA')
    WRITE(*,139)
139  FORMAT(/,T15,'ENTER XI,Y1,X2,Y2')
    READ(*,'(13)')X1,Y1,X2,Y2
    WRITE(*,102)
102  FORMAT(/,T15,'ENTER FILENAME ',$)
    READ(*,'(A20)')FNAME
    OPEN(3,FILE=FNAME,STATUS='NEW')
300  WRITE(*,110)
110  FORMAT(/,T15,'ENTER ROUGHNESS ',$)
    READ(*,'(I3)')SAM
    CALL DQUAD(0)
    CALL CGRAB(1)
    WRITE(*,200)
200  FORMAT(/,T15,'PRESS ANY KEY TO CONTINUE')
    READ(*,'(A)')DUM
    CALL CGRAB(0)
    CALL DQUAD(2)
    CALL CGRAB(1)
    WRITE(*,200)
    READ(*,'(A)')DUM
    CALL CGRAB(0)
    CALL ADDTWO(1,2,0)
    CALL SETWIN(X1,Y1,X2,Y2)
    MAX=IHISTO(BUF)
    CALL SAVDATA(0,200,250,SAM,BUF)
    WRITE(*,150)
150  FORMAT(/,T15,'TYPE 1 TO CONTINUE',
        /,T15,'TYPE 2 TO EXIT ',$)
    READ(*,'(II)')M
    IF(M.EQ.1) GOTO 300
    CLOSE(3,STATUS='KEEP')
ELSEIF(NUM.EQ.5) THEN
    WRITE(*,160)
160  FORMAT(/,T15,'ENTER OFFSET= ',$)
    READ(*,'(I3)')K
    CALL OFFSET(K)
ELSEIF(NUM.EQ.6) THEN

WRITE(*,170)
170 FORMAT(/,T15,'ENTER GAIN= '$)
READ(*,'(I3)')L
CALL GAIN(L)
ELSEIF (NUM.EQ.7) THEN
WRITE(*,180)
180 FORMAT(/,T15,'ENTER WORKING QUAD= '$)
READ(*,'(II)')QUAD1
WRITE(*,181)
181 FORMAT(/,T15,'ENTER DES. QUAD= '$)
READ(*,'(II)')QUAD3
CALL SUBTRACT(QUAD1,QUAD3)
ELSEIF (NUM.EQ.8) THEN
BSIZE=1024
WRITE(*,616)
616 FORMAT(/,T15,'ENTER QUAD.'$)
READ(*,'(II)')QUAD
WRITE(*,615)
615 FORMAT(/,T15,'ENTER FILENAME '$)
READ(*,'(A12)')FILENAME
RET=ITODSK(BSIZE,QUAD,FILENAME,BUFFER)
ELSE
CALL PEXIT
GOTO 201
ENDIF
GOTO 500
201 STOP
END
$ INCLUDE: 'FORINTF.H'
SUBROUTINE SAVDATA(QUAD,11,I2,SAM,BUF)
INTEGER*2 QUAD,Y1,Y2,X,Y,I1,I2
INTEGER*4 SUM(512),BUF(256)
INTEGER*2 MSUM(512),KSUM,Z,ISUM(512)
INTEGER*2 NSUM(512),AVE,SAM
INTEGER*4 TSUM,MAX
REAL*4 RX(256),RY(256),AMP(256)
CHARACTER DUM
CHARACTER*20 NAME
REAL*4 HIS(256),XIS(256)
PI=3.14159265
ISIGN=-1
M=3
N=256
DO 155 L=1,256
   HIS(L)=BUF(L)/100.0
155 CONTINUE
CALL ANGHIS(HIS,SAM,RMEAN,STD,HRMS,RMAX,S2)
IF(QUAD.EQ.0) THEN
   Y1=0
   Y2=511
ELSEIF (QUAD.EQ.1) THEN
   Y1=512
   Y2=1023
ELSEIF (QUAD.EQ.2) THEN
   I1=I1+511
   I2=I2+511
   Y1=0
   Y2=511
ELSEIF (QUAD.EQ.3) THEN
   I1=I1+511
   I2=I2+511
   Y1=512
   Y2=1023
ENDIF
   DO 20 I=1,512
      SUM(I)=0
20 CONTINUE
   KSUM=I2-I1+1
   DO 140 X = I1,I2
      DO 140 Y = Y1,Y2
         J=Y+1
         SUM(Y) = IPIXR(X,J)+SUM(Y)
140 CONTINUE
   DO 160 Y = 1, 512
      ISUM(Y)=SUM(Y)/KSUM
160 CONTINUE
   TSUM=0
   DO 164 Y=150,405
      TSUM=ISUM(Y)+TSUM
164 CONTINUE

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
AVE = TSUM / 256
DO 166 Y = 150, 405
   NSUM(Y) = ISUM(Y) - AVE
166 CONTINUE
DO 171 I = 1, 256
   J = I + 149
   MSUM(I) = NSUM(J)
   K = 128 - I
   W = 0.5 * (1 + COS((2 * PI * K) / 256))
   RX(I) = MSUM(I) * W
   RY(I) = 0
171 CONTINUE
CALL FFT(RX, RY, N, M, ISIGN)
DO 172 I = 1, 256
   AMP(I) = ((RX(I) / 256)**2 + (RY(I) / 256)**2)**0.5
172 CONTINUE
CALL FFTANG(AMP, YRMS, RAX, FOC)
WRITE(*, 200)
200 FORMAT(/, T15, 'SAVE HISTOGRAM DATA (Y/N)?' $)
READ(*, '(A)') DUM
IF (DUM.EQ. 'Y') THEN
   WRITE(*, 302)
   READ(*, '(A20)') NAME
   OPEN(4, FILE = NAME, STATUS = 'NEW')
   DO 205 I = 1, 256
      I1 = I - 1
      WRITE(4, 309) I1, HIS(I)
   309 FORMAT(13, F9.3)
   CONTINUE
   CLOSE(4, STATUS = 'KEEP')
ENDIF
WRITE(*, 306)
306 FORMAT(/, T15, 'SAVE FOURIER SPECTRUM (Y/N)?')
READ(*, '(A)') DUM
IF (DUM.EQ. 'Y') THEN
   WRITE(*, 302)
   FORMAT(/, T15, 'ENTER FILENAME ', $)
   READ(*, '(A20)') NAME
   OPEN(4, FILE = NAME, STATUS = 'NEW')
   DO 307 I = 1, 52
      FR = I * 3.8572
      WRITE(4, 308) FR, AMP(I)
   308 FORMAT(F5.1, F8.4)
   CONTINUE
   CLOSE(4, STATUS = 'KEEP')
ENDIF
WRITE(3, 34) SAM, RMEAN, STD, HRMS, RMAX, S2, YRMS, RAX, FOC
34 FORMAT(13, 2X, 8(F8.4, 1X))
RETURN
END
SUBROUTINE ANGHIS(RHIS,SAM,RMEAN,STD,HRMS,RMAX,S2)
REAL*4 RHIS(256),HMEAN,HRMS,RMEAN,STD
REAL*4 HSQUAR,HTOTAL,RMAX
INTEGER*2 I,J,SAM
HTOTAL=0.0
HSUM=0.0
HSQUAR=0.0
RSQUAR=0.0
RMAX=0
DO 21 I=2,255
   IF(RHIS(I).GT.RMAX) THEN
      RMAX=RHIS(I)
      LOC=I-1
   ENDIF
21 CONTINUE
DO 23 I=1,256
   IF(RHIS(I).NE.O.O)THEN
      HTOTAL=HTOTAL+RHIS(I)
      HSQUAR=HSQUAR+RHIS(I)**2
      HSUM=HSUM+1
   ENDIF
23 CONTINUE
HMEAN=HTOTAL/HSUM
HRMS=(HSQUAR/HSUM)**0.5
DO 30 I=2,255
   IF (RHIS(I).NE.0) THEN
      RAT=(RHIS(I)/HTOTAL)*100
      RSQUAR=RSQUAR+RAT*RAT
   ENDIF
30 CONTINUE
RMS=(RSQUAR/HSUM)**0.5
SUMM=0.0
SUMG=0.0
TWO=0.0
DO 24 I=2,255
   SUMM=I*RHIS(I)+SUMM
   SUMG=RHIS(I)+SUMG
24 CONTINUE
RMEAN=SUMM/SUMG
DO 25 I=2,255
   J=I-1
   DIF=J-RMEAN
   TDIF=DIF*DIF
   TWO=TDIF*RHIS(I)+TWO
25 CONTINUE
STD=(TWO/SUMG)**0.5
S2=STD/HRMS
RETURN
END
$INCLUDE: 'FORINTF.H'

SUBROUTINE FFTANG(AMP, YRMS, RAX, FOC)
REAL*4 YMEAN, YTOTAL, YSUM, YRMS
REAL*4 AMP(256), RAX, YSQUAR, FOC
YTOTAL = 0.0
YSUM = 0.0
YSQUAR = 0.0
DO 200 I = 5, 52
  YTOTAL = YTOTAL + AMP(I)
  YSQUAR = YSQUAR + AMP(I)**2
  YSUM = YSUM + 1
200 CONTINUE
YRMS = (YSQUAR / YSUM)**0.5
RAX = 0.0
DO 20 I = 5, 50
  IF(AMP(I) .GT. RAX) THEN
    RAX = AMP(I)
    FOC = I*3.8572
  END IF
20 CONTINUE
RETURN
END
SUBROUTINE FFT(X,Y,N,M,ISIGN)
REAL*4 X(1024),Y(1024)
REAL*4 PI2, SCL, ARG, S, C, T1, T2, ONE
ONE = 1.0
NV2 = N/2
NM1 = N-1
J = 1
DO 7 I = 1, NM1
   IF(I.GE.J) GOTO 5
   T = X(J)
   X(J) = X(I)
   X(I) = T
   T = Y(J)
   Y(J) = Y(I)
   Y(I) = T
5  K = NV2
6  IF(K.GE.J) GOTO 7
   J = J - K
   K = K / 2
   GOTO 6
7  J = J + K
C TO PERFORM COOLEY FFT ALGORITHM
C
PI2 = ISIGN * ATAN(ONE) * 8.0
DO 20 L = 1, M
   LE = 2**L
   LEI = LE / 2
   SCL = PI2 / LE
   DO 20 J = 1, LEI
   ARG = (J-1) * SCL
   C = COS(ARG)
   S = SIN(ARG)
   DO 20 I = J, N, LE
      IP = I + LEI
      T1 = X(IP) * C + Y(IP) * S
      T2 = Y(IP) * C - X(IP) * S
      X(IP) = X(I) - T1
      Y(IP) = Y(I) - T2
      X(I) = X(I) + T1
20   Y(I) = Y(I) + T2
RETURN
END

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
$INCLUDE : 'FORINTF.H'

SUBROUTINE SUBTRACT(QUAD1, QUAD3)
INTEGER*2 QUAD1, QUAD3
CHARACTER BUF1(512), BUF(512)
INTEGER*2 XI, Z1, Y1, TEMP
CALL DQUAD(QUAD3)
CALL SETIND(255)
CALL CLEAR(0, 7)
WRITE(*, 100)

100 FORMAT(/, T15, 'THRESHOLD LEVEL = '$)
READ(*, '(13)1') TEMP
XI = 0
Y1 = 0
Z1 = 0
DO 10 I = 1, 480
CALL R0WR(X1, QUAD1, BUF1)
DO 20 J = 2, 480
   K = J - 1
   I1 = ICHAR(BUF1(K))
   I2 = ICHAR(BUF1(J))
   I3 = ABS(I1 - I2)
   IF(I3.GT.TEMP) THEN
      I3 = 255
   ENDIF
   BUF(J) = CHAR(I3)
20 CONTINUE
CALL R0WW(Z1, QUAD3, BUF)
X1 = X1 + 1
Y1 = Y1 + 1
Z1 = Z1 + 1

10 CONTINUE
RETURN
END
VITA AUCTORIS

1963  Born in Hong Kong

1980  Received Secondary School Diploma at Tang King Po School, Hong Kong

1981  Received Grade 13 Diploma at Neil McNeil High School, Toronto, Ontario, Canada.

1985  Received the degree of Bachelor of Applied Science from the Department of Mechanical Engineering, University of Windsor, Windsor, Ontario, Canada.

1987  Currently a candidate for the degree of Master of Applied Science in Mechanical Engineering at the University of Windsor.