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On-Line Assessment of Surface Roughness through Fractal Geometry

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On-line Assessment of Surface Roughness through Fractal Geometry

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Abstract

On-line measurement of surface roughness is an important element in a Computer Integrated Manufacturing (CIM) environment. Current methods of contact measurement are not suitable as they interfere with the machining process. Optical methods, such as laser profilometry, in general, use expensive and large equipment, which pose difficulties in the implementation on the machine tool for on-line monitoring. This paper presents an optical area based surface characterization technique which applies fractal geometry and basic light scattering principles. The novelty in this approach is that the above principles are used to facilitate in-process measurement and control. A prototype of this system is developed and the experimental results are presented. The capabilities and future potential of this system are demonstrated.

Nomenclature

a: scaling constant in W-M function	N(s): Number of boxes of size s that lie within A
A: Set of points contained in the curve	Ra: Roughness Average in μm
D: fractal dimension	s: Size of boxes that are super imposed on A.
E: number of arguments in fBm	x: Distance in mm
fBm: fractional Brownian motion	W-M: Weinstrass Mandelbrot function
g: scaling constant in fBm function	α : constant
h: Height variation along the trace	ϕ_n : arbitrary phases
H: Parameter defining the fBm	μ : Mean of the pixel values in the image

1. INTRODUCTION

On-line process monitoring has been an active area of research as it is recognized as an essential part of a fully automated manufacturing system. Such a system would be essential in the future to produce products of high quality without compromising on productivity. One of the main parameters that is to be monitored during manufacturing is the surface finish of the product. The importance of on-line measurement systems in CIM environment calls for better and quicker systems that provide an estimate of surface roughness of the machined product. Literature survey [1-3] reveals that the important characteristics of on line surface roughness measurement systems are

- It should not interfere with the machining process
- It should operate reliably under varying conditions of machining
- It should be fast enough to operate under real time environment.

This paper presents the results obtained from developing an optical area based surface characterization technique. This new technique uses the theory of fractal geometry of the to estimate the surface roughness of the machined surface. In the past many researchers have worked on both using optical measurement methods and fractal dimension analysis to estimate the surface roughness [1-8]. The major limitation of these methods is that they used optical methods like laser profilometry to scan the surface line by line. Information obtained from individual surface profilometric measurements, very often fails to completely characterize the surface texture formed during machining and thus cannot be used to measure the true surface roughness on-line. In addition, these methods required large and expensive equipment, causing difficulties in their implementation as an on-line monitoring system. With respect to fractal methods, previous methods relied on images that were reconstructed from the data obtained from profilometer measurements. This process was computationally intensive which prohibits their use as an in-process surface monitoring system.

The work done here uses a new approach by performing an area based analysis of the image of the machined surface. The fractal dimension of the whole image is calculated and calibrated with the actual surface roughness. The paper is organized as follows: the theoretical background which forms the basis for this approach is presented followed by the description of the actual system. The experimental results are presented. It is followed by the analysis of their implications.

2. BASIC METHODOLOGY

2.1 FRACTAL GEOMETRY

Fractals are rough or fragmented geometric shape that can be subdivided in parts. Each part is approximately a reduced size copy of the whole [9]. In general terms, fractals are complex geometric objects which look similar to the original image under a range of magnification scales (i.e. they are self similar). Fractals also have the property of being

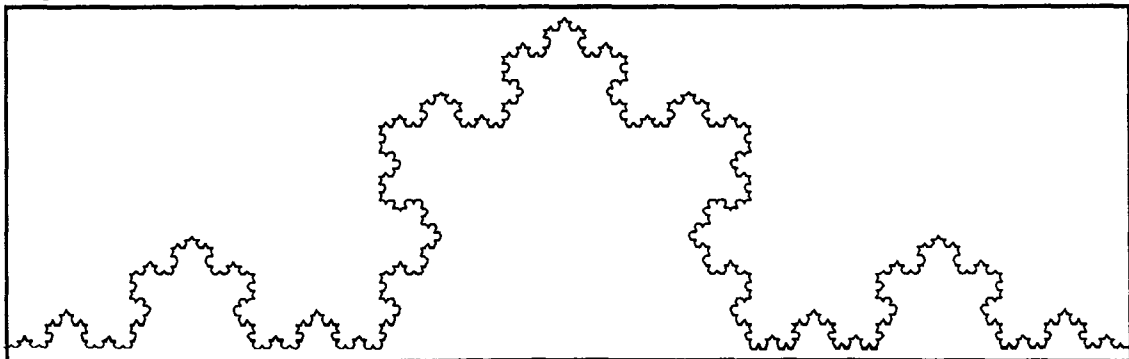


Fig 1. Example of a Fractal curve - Koch curve

continuous everywhere but not differentiable anywhere. Such a property is illustrated by an example as shown in Figure 1. The properties of this curve are extensively discussed by Mandelbrot [9].

Fractals can be described by scale invariant parameter called as Fractal Dimension. Fractal dimensions are basically numbers which attempt to quantify a subjective feeling on how dense the fractal occupies the metric space in which it lies. It is normally calculated using box counting algorithm.

The box counting algorithm is based on the following formula:

$$D = \lim_{s \rightarrow 0} \frac{\log(1/N(s))}{\log(1/s)}$$

where s = box size and N = number of boxes which lie within space of the curve for a given box size [9]. The slope must be calculated in the linear region of the curve to obtain the correct fractal dimension of the curve. The above method even though simple, is time consuming to calculate. Toth et al [12]. proposed an efficient algorithm to calculate the fractal dimension of digitized images. Based on their method the fractal dimension of the image is calculated, This fractal dimension calculator is incorporated in the image processing software. To expedite the calculation of the fractal dimension, the region in which the slope is linear is found and the values of N are calculated for those box sizes only.

2.2 FRACTAL GEOMETRY AS APPLIED TO ROUGH SURFACES

Fractal models provide a more realistic representation of the machined surfaces, as it is not based on Euclid geometry. As an example, a surface profile obtained through the vision system is shown in Fig. 2a. If the surface profile is obtained using equal magnification on both axes Fig. 2b is obtained. The surface profile does not look similar to the original image. The figure looks like an elongated version of the original image. However using different magnification scales on the axes we can obtain Fig. 2c which looks *similar* to the original profile. This property is known as self-affinity, where shapes are statistically invariant under transformations that scale different coordinates by different amounts[10]. Any model that is used to simulate the surface profile must satisfy the above property.

The Weierstrass - Mandelbrot **W-M** fractal function was proposed by Mandelbrot to model rough surfaces [9]. It is defined as

$$h(x) = \sum_{n=-\infty}^{\infty} \frac{(1 - e^{(2\pi j a^n x + \phi_n)})}{a^{n(2-D)}}$$

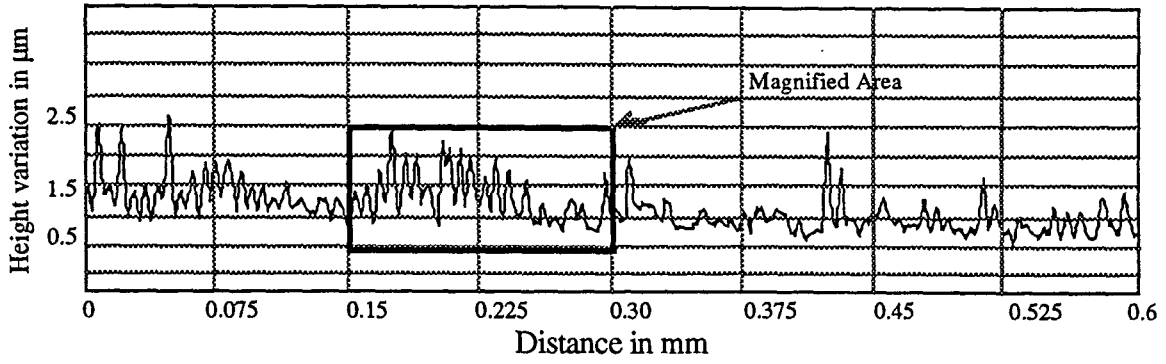
where

a = constant >1

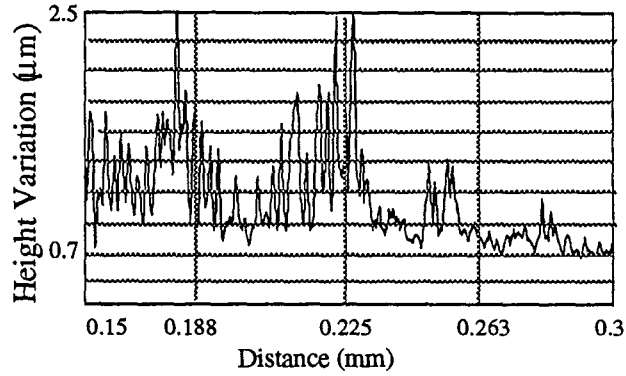
D = Fractal Dimension

ϕ_n = Arbitrary phases

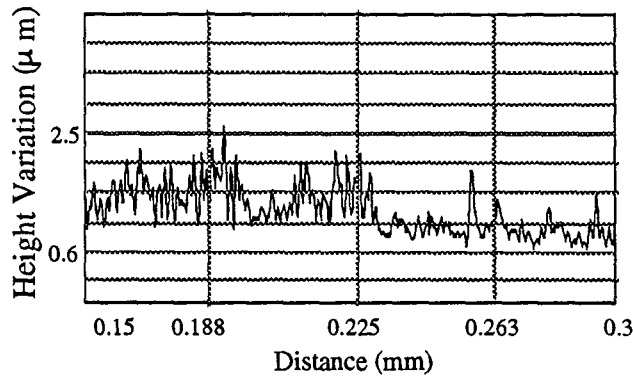
$h(x)$ = Height variation along the surface



(a) Example of a Surface Profile



(b) $x' = 2x$ and $h' = 2h$



(b) $x' = 2x$ and $h' = 0.8h$

Figure 2 Surface profile under different magnification scales on the x and h axes

The W-M function has all the above mentioned properties of a roughness profile. It is continuous everywhere, but nowhere differentiable. This is due to the fact that under different scales of magnification, more and more details of the roughness appear [13]. Consequently, the function is nowhere differentiable. The W-M function also possesses the following relation

$$h(gx) = g^{(2-D)}h(x)$$

where g is the scaling factor for x . From the above relation we see that the scaling for x and h are different and thus the W-M function is self-affine.

Brownian motion, commonly used for describing motion of a suspended particle in a fluid, can be modified such that it can be used to describe the roughness profile of a surface. The modified function is called fractional Brownian motion (fBm) [10] and is a commonly used function to describe and generate fractal surfaces. fBm curves are not self similar under equal magnification in all directions, but they are self affine, i.e., they look self similar under unequal scales of magnification in different directions. The statistics of fBm follow the relation

$$\langle (h(x_1) - h(x_2))^2 \rangle \propto |x_1 - x_2|^{2H}$$

where $\langle \rangle$ implies temporal average. The fractal dimension of fBm cannot be obtained using the definition of self-similar fractal dimension as the fBm is self-affine [14]. Voss showed that the fractal dimension is related to parameter H by the relation [11]

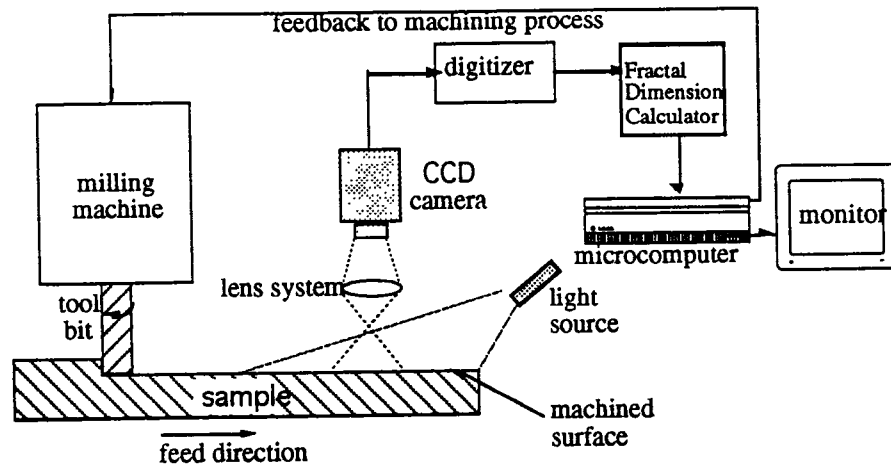
$$D = E + 1 - H$$

where E = number of arguments of the function $h(x)$. Therefore, fBm can be described completely by finding D of the self affine curve under correct measurement methods. Thus fractal geometry can be applied to estimate the surface roughness.

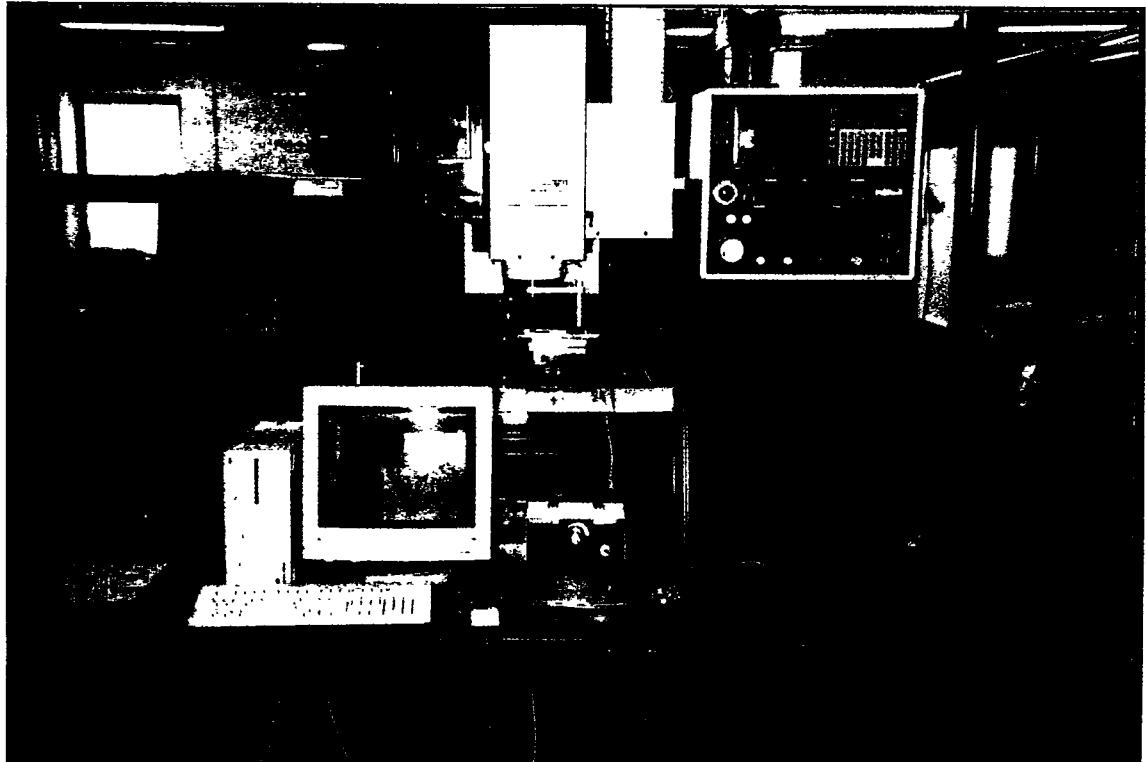
2.3. APPLICATION OF FRACTAL GEOMETRY

The image is obtained from the machined surface using a CCD camera and then analyzed by the micro computer to obtain the fractal dimension of the image. This fractal dimension is then used to estimate the surface roughness. This R_a value can then be used as a controlling factor in estimating the best machining parameters to produce the product with the required surface finish.

As illustrated in Figure 3a., a frame grabber is used to capture the image at the rate of 30 frames per second. This image is then analyzed using the NIH- Image, an image processing software. From the image we find the fractal dimension of the image. The fractal dimension of the image is calculated using modified version of the fast fractal dimension estimating algorithm developed by Toth et al [12]. By using the D values thus generated for surfaces of known R_a values, we can generate a calibration curve as illustrated in Figure 5. From that curve, under the same setup conditions, we can estimate the surface roughness of any similar surface by using the calibration curve.



(a) Basic Components of the Proposed Vision System



(b) Implementation of the proposed system on a MC-510 CNC Machining Center
 Figure 3. Design and Implementation of the Vision System

3. SYSTEM IMPLEMENTATION AND EVALUATION

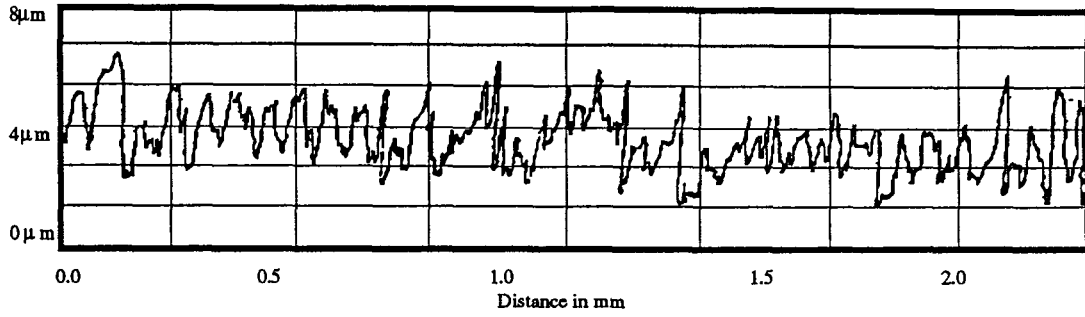
3.1. IMPLEMENTATION OF THE PROPOSED SYSTEM

To implement the proposed method a prototype system is used. The prototype system consists of a SONY CCD-IRIS camera, variable intensity light source, fiber optic cable to orient the light, a test stand to hold the samples and Macintosh IICI with modified NIH- Image software to calculate the fractal dimension directly. As shown in Figure 5 the test stand holds the machined aluminum sample. The surface is illuminated using the fiber optic cable connected to the variable intensity light source. The image is picked up by the camera and sent to the microcomputer through a frame grabber.

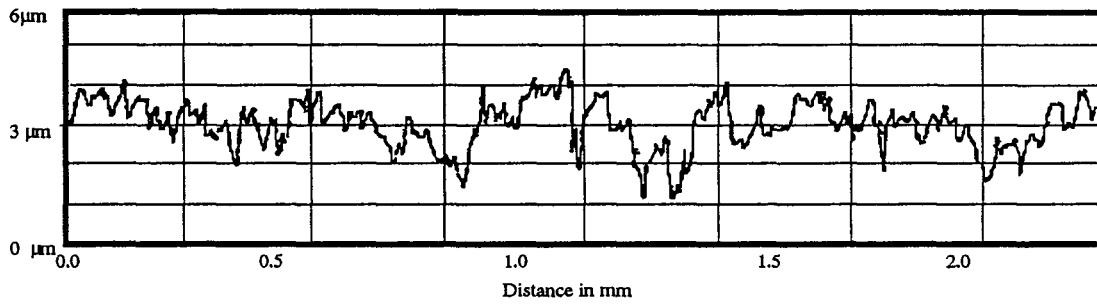
Fractal based approach is used to analyze the image. One of the main problem associated with fractal dimension approach is the time involved to calculate the fractal dimension. The normally used method is the box counting algorithm. An improved and fast method to calculate the fractal dimension was proposed by Toth et al. [12] . This approach uses sorted bits of the image bytes to find whether the particular point lies within the box of size 's'. The fractal dimension is found by calculating the slope at the linear region of the curve $\log(1/N)$ Vs. $\log(1/s)$. It was found by analyzing the machined surface images the curve was linear only for a range of box sizes. Therefore the fractal dimension is found by calculating N for only those box sizes. This effectively makes the calculation of fractal dimension almost instantaneous. Thus the fractal dimension can be used to determine the surface roughness on line. An implementation of the system on a CNC milling center is shown in figure 3b.

3.2. EXPERIMENTAL WORK

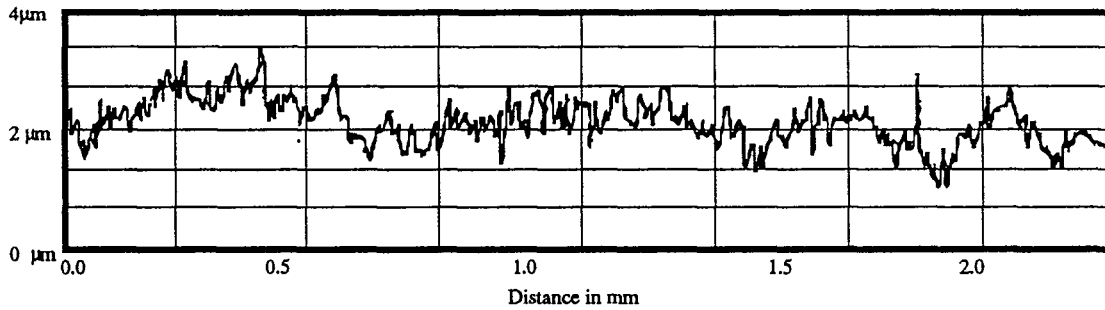
The surface roughness of four aluminum samples, machined under various cutting conditions, was found using Talysurf. The resulting profiles were digitized and their fractal dimension was obtained as shown in Figure 4. The results showed that the surface roughness is indeed related to the fractal dimension as expected from the theoretical observations. The image from these samples were recorded using a prototype setup, to test whether the system could be used as an on-line monitoring system. The fractal dimension of the machined surfaces were found and calibrated with the surface roughness. The resulting graph showed good correlation between the fractal dimension and the surface roughness. From this curve the surface roughness of any other sample under the same setup conditions can be found.



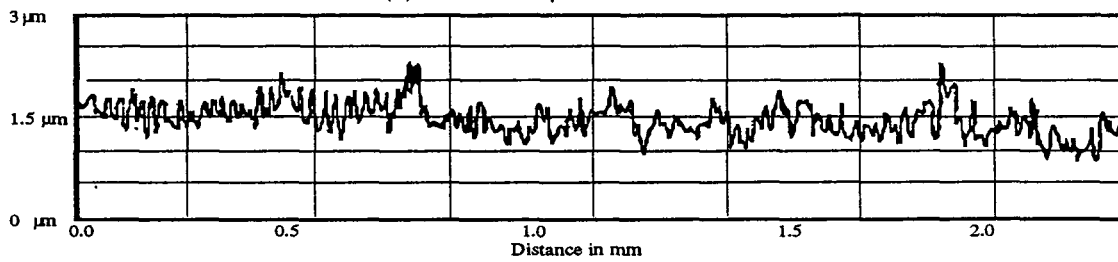
(a) $Ra = 0.7\mu\text{m}$ $D = 1.42$



(b) $Ra = 0.53\mu\text{m}$ $D = 1.34$



(c) $Ra = 0.36\mu\text{m}$ $D = 1.29$



(d) $Ra = 0.23\mu\text{m}$ $D = 1.21$

Figure 4. Variation of fractal dimension with respect to the surface roughness profiles

3.3. SENSITIVITY ANALYSIS

During machining, the image of the machined surface may be affected by the environment. Any practical on-line monitoring system must be stable under variation in the environmental conditions. The major variables that affect the output are

- ambient lighting
- incident angle of the light source
- horizontal orientation of the light source with respect to the machining direction
- intensity of the light source

The effect of these factors on the system performance can be guessed based on prior knowledge of the system and fractal geometry. It is known that a two dimensional object has an fractal dimension of 2 whereas a cube would have a fractal dimension of 3 [11]. Therefore the smoother the surface lower will be its fractal dimension. As it becomes rougher and rougher it will fill up the existing space and thereby increasing the fractal dimension. Ambient light increases the brightness level of the pixels and thereby removes the surface detail. This makes the surface look more rougher and thus will increase the fractal dimension. The variation in incident angle and the horizontal orientation of the light source is expected to bring out more or less details of the machined surface due to shadow effect, thus varying the fractal dimension. As the light source becomes more intense the overall image becomes brighter and thus resulting in increase in μ , where μ is the mean value of all the pixels in the image. This again is expected to increase the fractal dimension.

To practically estimate the effect of these variables on the proposed system a full factorial design with four variables at two level was done off-line on four different samples with known surface roughness.

TABLE 1 — Factorial Design with Four Variables

Factors under Investigation	High Level	Low Level
Horizontal orientation of light in degrees	55	45
Incident angle of light	20	10
Light source intensity	100%	80%
Ambient lighting	off	on

A fiber optic cable was mounted on a fixture so that the horizontal orientation and the incident angle of the light can be varied. The level light source intensity was varied by using two settings in the dial. The high level was set at the maximum position and the low

level is got by reducing the light source brightness to 80% of the maximum setting. Ambient lighting was produced by nine 34W fluorescent bulbs placed between 1.5m to 3m overhead of the experimental arrangement. Sunlight was not allowed to reach the workpiece throughout the experiment.

The main effects of the variables were found using the standard t-test and F-test was conducted to find the sensitivity of the system with respect to the surface roughness of the specimen. The results are tabulated below. The standard error in the measurements was found to be 0.00926. Those effects whose values are lower than the standard error are assumed to be caused by the natural variation in the measurements and are neglected. From the t-test it was found that the incident angle and interaction effects between the variables can be ignored with confidence level of 95%. From the F-test, it was concluded that the system was very sensitive to changes in the surface roughness as the F-ratio was high for surface roughness variation

TABLE 2 RESULTS FROM THE F-TEST

Source of variation	Sum of Squares	Degree of Freedom	Mean Square	Ratio
Grand Average	87.50	1	87.50	
Environmental Conditions	0.0059	3	0.002	12.1
Surface roughness	0.098	3	0.033	198.3
Residuals	0.0015	9	0.0002	
Total		15		

4. DISCUSSION OF RESULTS

The results from the factorial design are analyzed below in the order of their importance. An important finding is that there is practically no interaction effects between the different factors that affect the sensitivity of the system.

(a) *Ambient Lighting* ($k_4 = 0.05$)

Among all other variables variation in ambient lighting conditions caused the most variance in the results. Increase in ambient light removes surface detail of the machined surface and thus tends to increase the fractal dimension. Therefore it is very important that the system is calibrated under similar lighting conditions as expected during the actual machining.

(b) *Source Light Intensity* ($k_3 = 0.028$)

The next important variable is the intensity of the light source. Similar to the variation in ambient light, increase in intensity of the light source makes the image more flat and thus the fractal dimension increases. But the light source intensity can be controlled and for small variations in the light source the fractal dimension is not expected to vary by large amount.

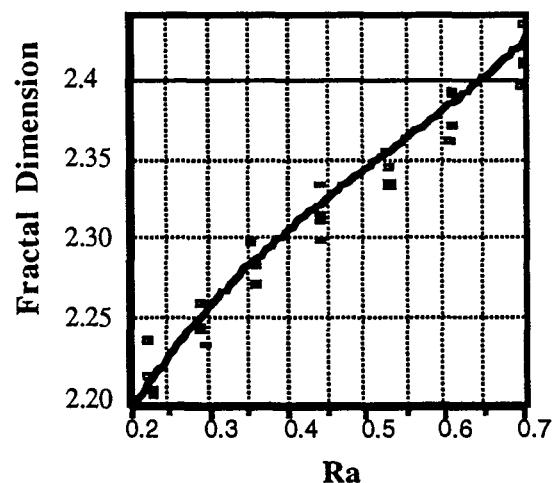
(c) *Horizontal orientation of light source* ($k_1 = 0.027$)

Variation in orientation of the light source with respect to the machining direction varies the output. This is due to the anisotropic nature of the milled surface. Thus the variation in the surface become more clearer or hidden according to the orientation of the light source. Again this requires that the system be properly calibrated. This also requires that the camera orientation system which makes sure that the camera follows the tool path be accurate. The solution is to control the position of the camera by a computer controlled stepper motor. The computer gives the commands based on the G-code program. The fixtures for such a system has already been made.

(d) *Incident angle of the light source* ($k_2 = 0.017$)

Under a confidence level of 95% this effect can be ignored for small variations in the incident angle. This maybe due to the fact that slight variations in the incident angle do not affect the image to produce a measurable variance in output. This result makes the system more reliable if the depth of cut is not constant and the light source need not be adjusted.

Thus this system can be effectively used to estimate surface roughness on line. The system will provide an cost effective and practical way of determining surface roughness in an actual machining environment.



$$Ra = 1.9875 + 1.3315D - 1.8135D^2 + 1.1464D^3 \quad \text{Correlation Coefficient} = 0.90$$

Figure 5. Calibration curve relating Fractal Dimension with Ra value

5. CONCLUSIONS

A prototype system is developed to perform surface roughness measurements using an area based fractal approach which makes it especially suitable for on-line process monitoring. A functional calibration curve which relates the fractal dimension of the surface

to the surface roughness was constructed in this study. The close correlation between the fractal dimension and surface roughness shows that the developed vision system provides a cost effective method for on-line monitoring. One of the significant findings in this study is that the calculated fractal dimension is sensitive enough to detect the variation in the surface finish even under different ambient conditions. The challenge in implementing this system is that the calibration process should be done under the same conditions that exist in the machining environment.

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