Mansoura Engineering Journal

Volume 35 | Issue 3 Article 5

11-23-2020

A Novel Light Sectioning Vision System for a Three Dimensional Surface Roughness Assessment.

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Recommended Citation

Abouelatta, Ossama (2020) "A Novel Light Sectioning Vision System for a Three Dimensional Surface Roughness Assessment.," *Mansoura Engineering Journal*: Vol. 35 : Iss. 3 , Article 5.
Available at: https://doi.org/10.21608/bfemu.2020.125069

Mansoura Engineering Journal, (MEJ), Vol. 35, No. 3, September 2010. M. 14

A NOVEL LIGHT SECTIONING VISION SYSTEM FOR A THREE DIMENSIONAL SURFACE ROUGHNESS ASSESSMENT

نظام قطاع ضوئي ورؤية بالحاسب جديد لتقييم خشونة السطح في الاتجاهات الثلاث

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الخلاصة: تعتمد طرق قياس خشونة الأسطح القياسية بدرجة كبيرة على أجهزة القياس بواسطة المجس والتي لها مرونة محدودة في التعامل مع قياس خشونة الأجزاء المختلفة. ومن ناحية أخرى، تتميز تقنيات القياس الضوئية والغير تلامسية بدرجة كبيرة عند قياس وتوصيف الأسطح الهندسية المعقدة والدقيقة عن مثيلاتها من الطرق الأخرى. وتعتمد هذه الدراسة تقديم طريقة جديدة لقياس خشونة الأسطح في الاتجاهات الثلاث بدمج طريقة ميكروسكوب القطاع الضوئي مع نظام الرؤية بالحاسب. وتتميز هذه الطريقة بأنها غير تلامسية وسريعة وفي نفس الوقت رخيصة. وقد تم إنشاء نسخة مبدئية من برنامج، يسمى *SR3DVision*، لكي يدير عملية قياس خشونة الأسطح في الثلاث اتجاهات. واستخدم ميكروسكوب قطاع ضوئي لعرض منحنيات الخشونة للعينات المراد قياسها، كما استخدم نظام للرؤية بالحاسب لالتقاط صور جانبية متعاقبة لمنحنيات الخشونة هذه. وقد تم كتابة وإنشاء هذا البرنامج باستخدام برنامج الماتلاب خصيصا بغرض تحليل الصور الملتقطة من خلال أربعة وحدات رئيسية وهي: وحدة التحكم في عملية القياس، وحدة استخلاص منحنيات أو أسطح الخشونة، وحدة حساب خشونة الأسطح في الاتجاهين، ووحدة حساب خشونة الأسطح في الاتجاهات الثلاث. وقد تمت معايرة النظام للقياس بواسطة الوحدات المترية، كما تمت التحقق من دقة عمليات القياس باستخدام عينات قياسية. وقد استخدم هذا النظام لقياس بعض العينات المشغلة باستخدام عمليات تشغيل مختلفة وقورنت نتائج القياس بنتائج برامج جاهزة وتم التحقق من دقة النظام حيث أثبتت نتائج المقارنة أن الفروق كانت في حدود ±4,5%.

Abstract

Standard roughness measurement procedures depend heavily on stylus instruments which have only limited flexibility in handling different parts. On the other hand, optical non-contact techniques are very interesting for 3D characterization of sensitive and complex engineering surfaces. In this study, a new approach is introduced to measure surface roughness in three dimensions by combining a light sectioning microscope and a computer vision system. This approach has the advantages of being non-contact, fast and cheap. A prototype version of a user interface program, currently named *SR3DVision*, has been developed to manage three dimensional surface roughness measurements. A light sectioning microscope is used to view roughness profiles of the specimens to be measured and the vision system is used to capture images for successive profiles. This program has been totally developed in-house using Matlab™ software to analyze the captured images through four main modules: (Measurement controller, Profile or surface extraction, 2D roughness parameters calculation and 3D roughness parameters calculation). The system has been calibrated for metric units and verified using standard specimens. In addition, the system was used to measure various samples machined by different operations and the results were compared with a commercial software and a web-based surface metrology algorithm testing system. The accuracy of the system was verified and proved to be within ±4.8% compared with these systems.

Key words

3D surface roughness, Computer vision, Light sectioning

Accepted September 30, 2010.

1 Introduction

The development of new industries has led to a requirement for super-smooth surfaces and for the ability to measure surfaces of industrial parts accurately; therefore, the measurement of engineering surface roughness is becoming increasingly important [1]. Many methods of measuring surface finish have been developed ranging from the simple touch comparator to sophisticated optical techniques [2]. Optical methodology and computer vision systems are the most common methods among the developed researches [3]. Computer vision was also implemented to measure surface roughness. Computer vision systems offers the advantages of the optical techniques, which tend to fulfill the need for quantitative characterization of surface topography without contact, whilst vision systems is considered relatively cheap and fast.

Several investigations have been performed to inspect surface roughness based on optical surface roughness measurements. A noncontact three-dimensional optical profiler for measuring surface roughness is described by Wyant et al. [4], based on a reflection microscope and Mirau interferometer. Besides, a general scheme for an on-line, non-contact, optically based inspection machine has been developed by Jolic et al. [5]. Yilbas and Hasmi [6], introduced an optical system for surface roughness measurement, based on an He-Ne laser beam and a fibre optic probe, used to scan the surface. A linear relationship exists between the R_a values and the standard deviation of Gaussian function (SDGF) of the reflected beam intensity. The greater are the SDGF values the greater is the surface roughness. One can say that spectral interferometry provides a simple method for measuring average roughness of the surfaces in the scale of optical wavelengths [7].

On the other hand, an approach based upon solving the inverse problem of light scattering by model-based scatterometry has been proposed by Hertzsch et al. [8] for the near-process inspection of turned surfaces. In the range of precision engineering ($R_a \leq 1.5$ μm), the mean profile of the dominant periodic component can be measured optically without scanning and without resorting to comparator standards. An original low cost integrated system using a planar light scanning technique in measuring the surface contour of three-dimensional objects has been investigated and an algorithm of processing the measured bit-map data into a format that could be input readily to a CAD system has been developed [9].

Results of the measurement of surface roughness using angular speckle-correlation on machined surfaces are presented in Persson [10]. Surfaces of approximately $1.6 < R_a < 6.3$ μm have been measured, the surfaces being classified in the same manner as when using a stylus instrument. Angular speckle correlation is a technique that allows in-process measurement of the roughness of surfaces on machined surfaces. An experimental approach for surface roughness measurement based on the coherent speckle scattering pattern caused by a laser beam on the machined surfaces (grinding and milling) is presented by Dhanasekar et al. [11].

On the other hand, computer vision was implemented to measure surface roughness by many researchers. Gadelmawla et al. [12] introduced a system to capture an image for a surface and then to extract the roughness heights from the captured image. This system capable of measuring surface roughness in either 2D or 3D domains. Gadelmawla [13] presented an approach for surface roughness characterization using computer vision and image processing techniques based on the gray level co-occurrence matrix. A new parameter called maximum width of the matrix is introduced to be used as an indicator for the surface roughness. An inexpensive machine vision system was demonstrated by Gupta and Raman [14] to compute non-contact, optical parameters for the online characterization of surface roughness of machined surfaces. Their experimentation revealed that the vision parameters can discriminate different surface roughness heights and are insensitive to changes in ambient lighting and speed of rotation during measurement. A surface roughness measurement technique for the on-machine measurement of the roughness of machined surfaces, based on the measurement of scattered light patterns and the statistical analysis of the light intensity distribution, has been proposed in Kim et al. [15]. The standard deviation of the scattered light pattern is nearly in proportion to the surface roughness. Measurements obtained using this method are within 10% of those obtained using a common contact method.

Unlike the stylus instruments, the optical techniques and computer vision systems have the advantages of being non-contact and are capable of measuring an area from the surface rather than a single line. Further the procedure is an in-process approach which is amenable for automation. Lee et al. [16-17] presented a system for measuring the surface roughness of turned parts using a computer vision system. Compared with the stylus method, the computer vision system constructed is a useful method for measuring the surface roughness faster, at a lower cost, and with lower environmental noise in manufacturing process. Ho et al. [18] proposed a method using an adaptive neuro-fuzzy inference system to establish an accurate estimation of surface roughness based on texture features of the surface image. Ngan and Tam [19], investigated a non-contact costly low approach suitable for on-site polishing inspection based on computer vision and image analysis. The results are promising and show that the proposed approach could be practical and robust. Based on the surface image features, a parameter called magnification index has been estimated by Kumar et al. [20] using regression analysis, for original images and for a magnified quality improved images. Finally, a comparison has been carried to establish correlation between magnification index and surface roughness. Al-Kindi and Shirinzadeh [21], presented a methodology for using machine vision data to acquire reliable surface roughness parameter measurement using standard and non-standard roughness parameters. The overall acquired results indicate that vision systems are a valid source of data to obtain both amplitude and spacing roughness parameters with confidence using the proposed methodology.

The use of light sectioning method combined with computer vision is suggested by many researchers. In the recent past, higher levels of automation in the shop floor has focused the attention on the application of fast, reliable and cost effective procedures for evaluating surfaces of medium finished parts. Light sectioning methods are considered as an optical technique, which was initially proposed by Schmaltz [22] to get the roughness profile of surfaces. A 2D surface roughness measurement system was designed with a light-sectioning microscope and the corresponding software was developed by Shou-Bin and Hui-Fen [23]. Their experimental results showed a feasible method for surface roughness measurement. A design of an optical instrument for 2D surface roughness measurement was demonstrated by Shou-Bin and Hui-Fen [24].

Based on these principles, a commercial optical instrument has been developed whose measurement height is in the range of 0.4-120 μm. Light sectioning of an object surface uses the line deformation imaged to compute the object profile was used by Lewandowaki and Desjardins [25]. Kiran et al. [26] covered in brief few finish assessment methods of medium rough surfaces using a standard vision system in order to achieve quick estimation of the finish of medium rough surfaces. Matsumoto et al. [27], proposed a profile measurement system with light sectioning, which is available to detect step profiles on objects. The performance of this system was confirmed by experiments, in which step profiles of objects at a distance of 500 mm could be measured. In a previous work, Elhamshary et al. [28], introduced a system to measure two dimensional surface roughness by combining a light sectioning microscope and a computer vision system. The system was used to measure machined samples and the results were compared with the measurements of a stylus instrument.

The aim of this work is to introduce a new non-contact system for automatic three dimensional measurement of surface roughness by utilizing a light sectioning microscope and a computer vision system. Consequently, amplitude roughness parameters in three dimensions as well as most of the two dimension roughness parameters can be calculated by the introduced system.

2 Experimental setup

The introduced system consists of two major parts, hardware and software. A photograph of the system is shown in Fig. 1. The hardware consists of four items: personal computer (PC), a light sectioning microscope, a vision system and a precision table of Nikon Measurescope-10 derived by a stepper motor and its controller. The PC is an IBM-compatible personal computer with Pentium processor and Windows operating system. The light sectioning microscope is supplied with a suitable set of magnification lenses to produce magnified roughness profiles for surfaces under investigation. The vision system consists of a JVC color video camera (CCD) and an ELF-VGA frame grabber provided with capturing software to capture images acquired by the CCD camera. The CCD camera is fixed on the eyepiece of the light sectioning microscope using a special holder designed to provide an accurate alignment between the camera and the image reflected by the microscope. The frame grabber is fitted inside the PC and connected to the CCD camera. It is used to digitize the analogue image, produced by the CCD camera, into 760×570 pixels with 16 bits of color.

A specially developed program, named *SR3DVision*, has been fully developed in-house using Matlab™ software and the provided image processing toolbox, to analyze the captured images. The *SR3DVision* program consists of four modules with a graphical user interface, which are: Measurement controller, profile or surface extraction, 2D roughness parameters calculation, and 3D roughness parameters calculation. All modules can be executed from the main interface, Fig. 2.

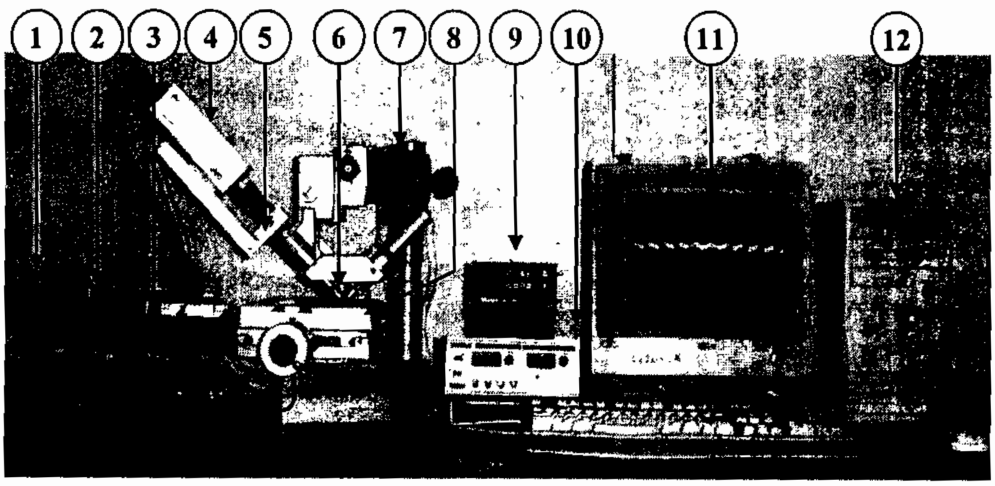


Fig. 1. Photograph of the introduced system.

1. Stepper motor.
2. Coupling.
3. Stepper motor controller.
4. CCD camera.
5. CCD camera holder.
6. Standard specimen.
7. Light section microscope.
8. Precision X-Y table.
9. Display counter.
10. Power supply.
11. Capturing software.
12. Personal computer.

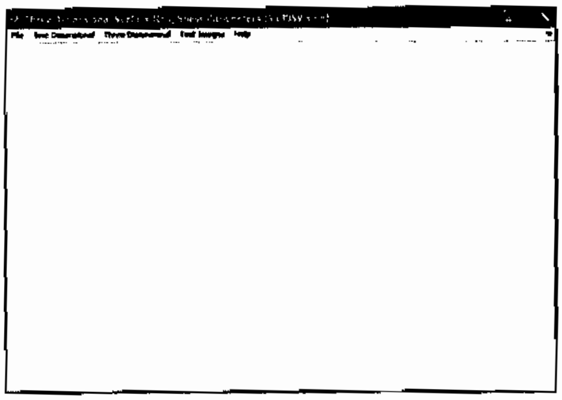


Fig. 2. Main interface of SR3DVision program.

The first module *(MeasControl)* is used to control the measuring process via stepper motor and its controller [29]. After starting measurements, the *x-y* table is automatically moved forward by 20 μm to eliminate backlash from the driving system. Next, the user is prompted to enter data file name, number of traces *(NTraces)* and the sampling interval Δy. These processes repeated *NTraces* times to produce a *NTraces* images.

The second module *(ProfileExtract)*, Fig. 3, is used to extract the *x-z* coordinates of the roughness profiles from the captured images by performing various image processing and computer vision algorithms. Through this module, each captured image is opened and analyzed to extract the 2D roughness profile, then the *x-z* coordinates of the extracted profile is saved to an ".SDF" file for further use by the *SR3DVision* program or other commercial software. On the other hand, this module can be used to extract the *x-z* coordinates of the successive profiles from the captured images. The *x-z* coordinates of the extracted profiles are saved to an ".SDF" file for further use by the *SR3DVision* program or other commercial software.

The third module (*RP2DCalc*), Fig. 4, is used to calculate the standard and non-standard 2D roughness parameters from the SDF file produced for each image by the second module [30-31]. In addition, this module is used to view the 2D surface roughness profile extracted from each image.

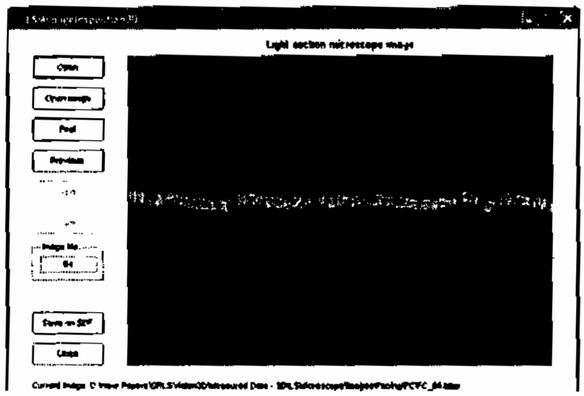


Fig. 3. Profile extraction module (ProfileExtract).

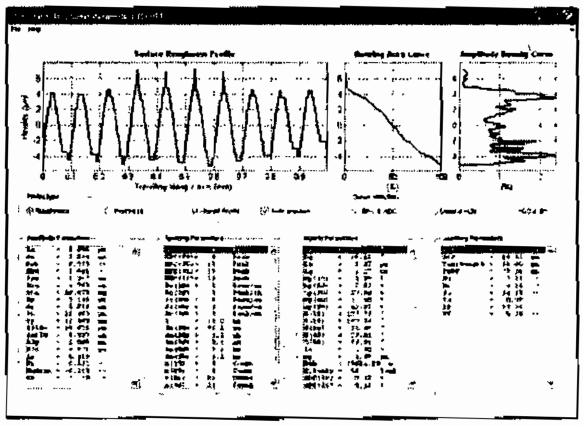


Fig. 4. Two dimensional surface roughness parameters calculation module (RP2DCalc).

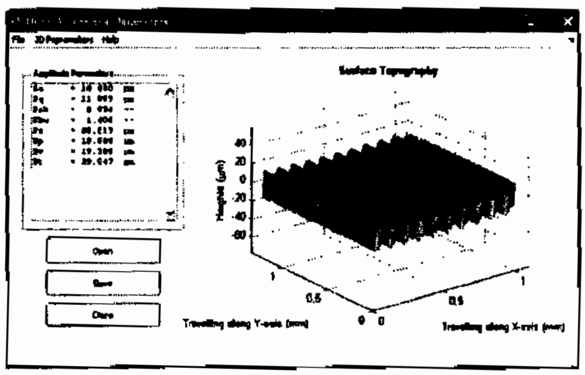


Fig. 5. Three dimensional surface roughness parameters calculation module (RP3DCalc).

The fourth module *(RP3DCalc)*, Fig. 5, is used to calculate the 3D roughness parameters [32] from the SDF files produced for all images by the second module. In addition, this module is used to view the 3D surface topography extracted from all captured images.

3 Procedures of work

To calculate the 3D surface roughness parameters and to visualize the 3D surface topography by the introduced system, the specimen to be measured is positioned on the table of the light sectioning microscope under the projected light. The focus is adjusted until the roughness profile appears clear on the screen of the capturing software (ELF-VGA). After selecting a suitable section, the capturing software is used to capture an image for the viewed profiles and to save it to a bitmap image file (BMP). This step is repeated *NTraces* for 3D surface roughness measurement. Finally, the captured image is opened by the *SR3DVision* program, then the processing algorithms are applied. The roughness parameters of the extracted profile can be calculated by selecting Calculate 2D or 3D parameters from the main module, which display the second and third modules, as shown in Fig. 4 and Fig. 5, respectively.

4 Processing algorithms

Image processing and computer vision algorithms are applied to analyze the captured images and to extract the roughness profiles as shown in Fig. 6. First, the algorithms check the depth of color in the opened image. If the image is colored, the software converts it to grey scale. Then, a global threshold is calculated to convert the grey scale image into a binary image (Black and white image). The upper and lower profiles are traced by locating upper and lower boundaries of the binary image. Finally, a calibration factor is applied to the extracted profiles in order to calculate the actual x and z coordinates (See Section 5).

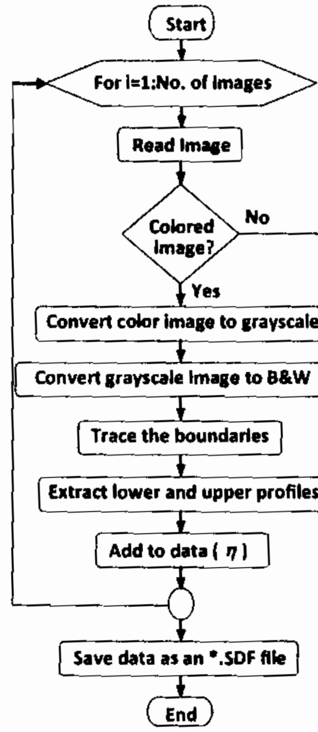


Fig. 6. Flowchart of the image processing algorithm used to extract surface heights data from the light sectioning profiles.

5 System calibration

The system has been calibrated for light sectioning microscope lens in both x-direction (horizontal resolution) and z-direction (vertical resolution). A standard specimen produced by American Optical Company-Buffalo, was used to calibrate the system for horizontal resolution. The specimen has 2 mm scale divided into units of 0.01 mm. A light section microscope lens was used to capture an image for the scale of the standard specimen and the number of divisions was counted for each image to calculate the corresponding field of view as shown in Table 1.

Table 1: Lens's specifications and the horizontal and vertical resolutions of the system

Lenses pair	Lens's focal length (mm)	Range of R_t (µm)	Range of R_a (µm)	Horizontal field of view (mm)	Horizontal resolution (µm/pixel)	Vertical resolution (µm/pixel)
1	25	10 - 80	2.5 - 20	1.8	2.3684	1.2550
2	13.9	6.3 - 20	1.25 - 5	1.0	1.3158	0.9343
3	8.2	3.2 - 10	0.63 - 2.5	0.6	0.7895	0.4967
4	4.3	1.6 - 3.2	0.32 - 0.63	0.3	0.3947	0.2647

Because the implied vision system produces images sized to 760×570 pixels, the horizontal resolution for each lens was calculated by dividing the value of the field of view (in μm) by the width of the captured image (760 pixels). The horizontal resolution (H), for example, a lens of 13.9 mm focal length can be calculated as follows:

Horizontal resolution (H) =

Field of view/Width of the captured image

= 1000/760 = 1.31579 μm/pixel

On the other hand, another standard specimen (Handysurf E-10A, Advanced Metrology Systems. Limited, Leicester, UK) has an arithmetic average roughness R_a = 2.97 μm and peak to valley height roughness parameter R_t = 11.72 μm was used to calibrate the system for the vertical resolution. Fig. 7 and Table 2 show a sample roughness profile of the standard specimen (4 mm length) obtained by a Surftest SJ201-P instrument connected to a personal computer. At least twenty images were captured for two standard specimens, then a two roughness profiles (upper and lower) were extracted by the *SR3DVision* program. Because the captured profiles may not be exactly horizontal, the least square method was applied to the extracted profiles to remove any inclination in the surface. The maximum peak to valley height was calculated (in pixels) for each profile, then the average value was taken. The vertical resolution (V) was calculated by dividing the actual value of R_t by the calculated average as follows:

Vertical resolution (V) = $10.95/R_t$

= 0.9343 μm/pixel

Table 1 summarizes the horizontal resolution (H) and vertical resolution of the system for a pair of light section microscope lens.

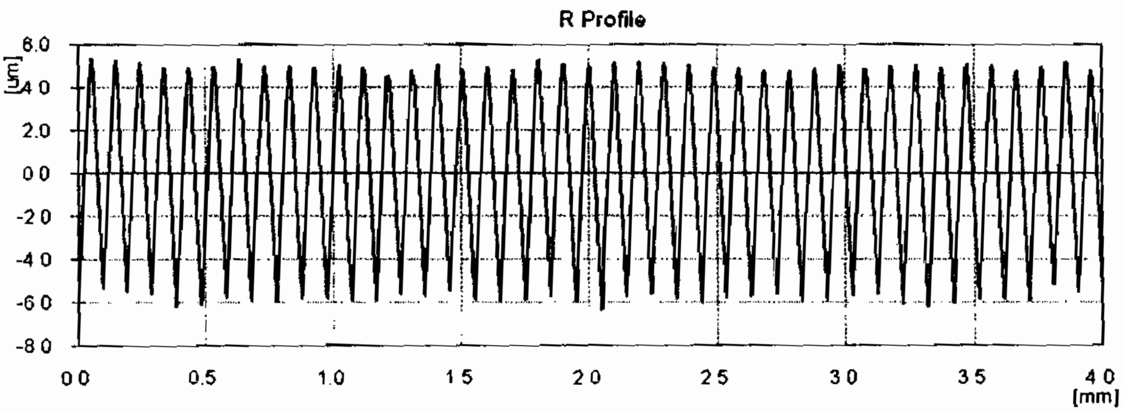


Fig. 7. Standard specimen measured by a Surftest SJ201-P.

Table 2: Surface roughness values of standard specimen measured by a Surftest SJ201-P

Parameter	Value
Average roughness height, R_a (μm)	2.97
Ten-point height, R_z (μm)	11.3
Root mean square roughness, R_q (μm)	3.37
Maximum peak to valley height, R_t (μm)	11.72
Maximum height, R_p (μm)	5.15
Peak count, RP_c (Peak/cm)	102.5
Average roughness height, R_{mr} (%)	15
Mean from 3[rd] highest peak to 3[rd] lowest valley, R_{3z} (μm)	10.97
Mean spacing of profile irregularities, RS (μm)	97
Mean spacing of profile irregularities, RS_m (μm)	98

6 Parameter calculation algorithms

Eight parameters for characterizing the amplitude parameters of surfaces are specified here. Amplitude parameters in three dimensions were calculated according to the flowchart shown in Fig. 8. At first, a least square mean plane was applied so that the sum of the squares of asperity departures from this plane is a minimum.

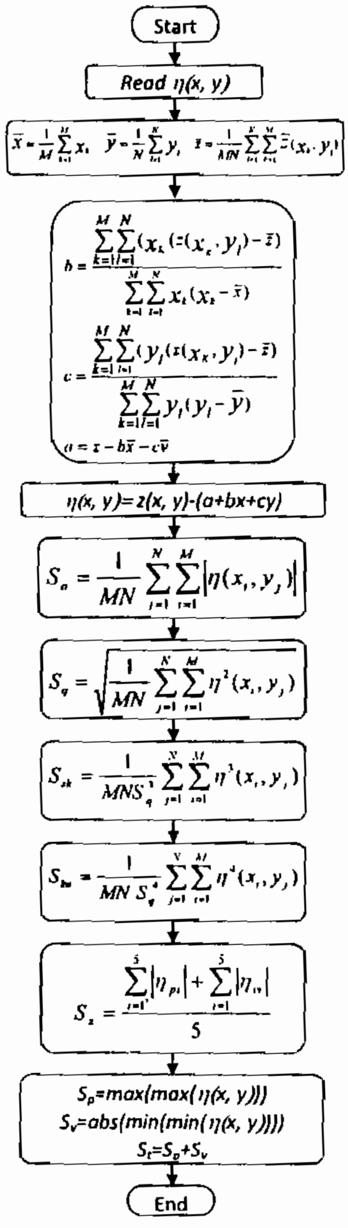


Fig. 8. Application of least square mean plane and 3D amplitude parameters calculation.

The least squares mean plane is unique for a given surface and it minimizes the root mean square height in comparison with other planes. For a given surface $z(x, y)$, its linear or first order least squares mean plane may be defined by $f(x,y) = a + bx + cy$ where a, b, c are the coefficients to be solved from the given topographic data. The calculated roughness parameters in three dimensions are: average roughness (S_a), root mean square roughness (S_q), skewness (S_{sk}), kurtosis (S_{ku}), ten-point height (S_z), maximum height (S_p), minimum Valley (S_v), maximum peak to valley height (S_t).

Ten point height of the surface (S_z) is an extreme parameter defined as the average value of the absolute heights of the five highest peaks and the depths of the deepest pits or valleys within the sampling area. A problem arises when calculating this parameter with digital computers, i.e. the definition of summits and valleys of areal topographic data [33]. They are more ambiguous compared with the definition of peaks and valleys of the profile data. Firstly, a summit may be defined within four nearest neighbors or eight nearest neighbors or contour-based summit. Secondly, the ridges, saddles, valleys and local undulations around the highest summit may adversely affect the ability to find the second and subsequent highest summits. Even for the contour-based summit, a problem arises as to whether only one summit should be defined on a ridge or not. Although a method to identify summits, flats, straits and ridges has been proposed, the algorithm still relies on the size of neighboring area [34-35]. Thus all the problems in defining the summit are concentrated on the extent of the neighboring area within which a summit should be defined. By using different definitions, the number of summits and the average height of the summits would be different. Anyway, the method of extracting summits, flats, straits and ridges that proposed by Peucker and Douglas, is used in this study as shown in Fig. 9.

7 System verification

To verify the accuracy of the introduced system, twenty images for different sections in each of the two standard specimens were captured and processed by the *SR3DVision* program to extract their roughness profiles and to calculate the 2D roughness parameters. The averages of R_a and R_t for the forty images were calculated and compared with the actual values of the two standard specimens (Specimen I: Handysurf E-10A, Advanced Metrology Systems, Leicester, UK; Specimen II: Surftest SJ-201P, Mitutoyo, Japan), as shown in Table 3. The percentage of differences between the actual and the measured values were within ±4.5%. Table 4 shows the calculated three dimensional roughness parameters, obtained by both the third module of the *SR3DVision* program and a commercial software, for an area of the standard specimens. A Web-based surface metrology algorithm testing system (http://syseng.nist.gov/VSC/jsp), was used to verify the *SR3DVision* program. This system includes surface analysis tools and a surface texture specimen database for parameter evaluation and algorithm verification. It was found that the maximum difference between the results of the two software is less than 4.8% for ten-point height of the surface (S_z). This may be due to the method of ten-point height calculation presented here. The difference percentages for the other parameters are less than 3.13%.

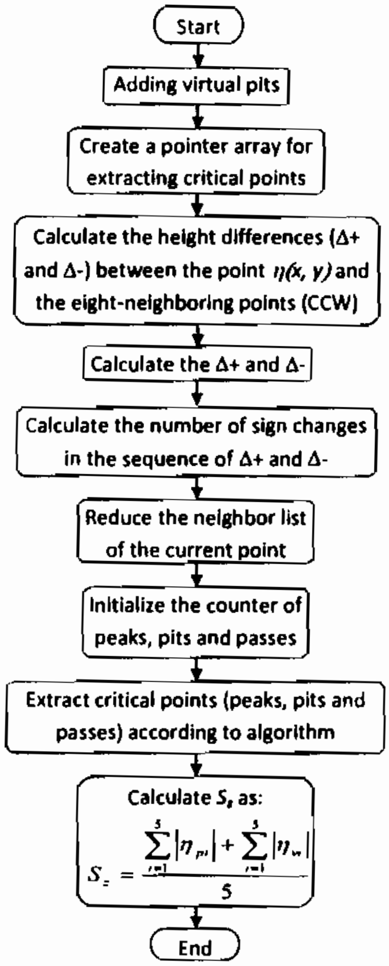


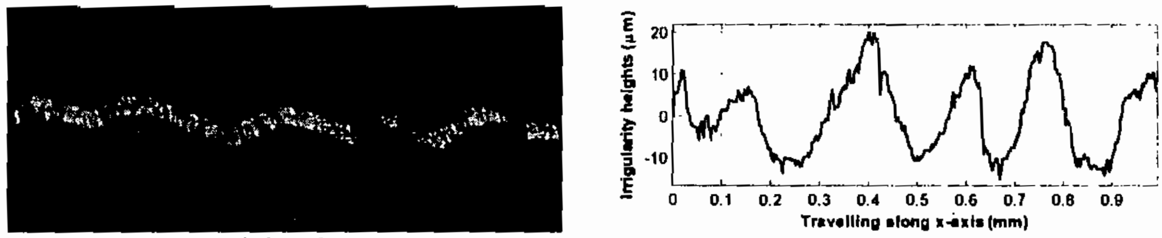
Fig. 9. Flowchart of Sz parameter calculation based on extraction of critical points (Peucker and Douglas, 1975; Pfaltz, 1976; and Wolf, 1991).

Table 3: Actual and calculated roughness parameters for the two standard specimen

Standard Specimen	Average roughness height R_a (μm)			Maximum peak to valley height R_t (μm)			Accuracy (%)
	Actual	Ave.	Diff. (%)	Actual	Ave.	Diff. (%)	
I	2.97	2.98	±0.50	11.72	12.10	±3.77	±3.77
II	2.97	2.92	±1.82	13.21	12.91	±4.46	±4.46

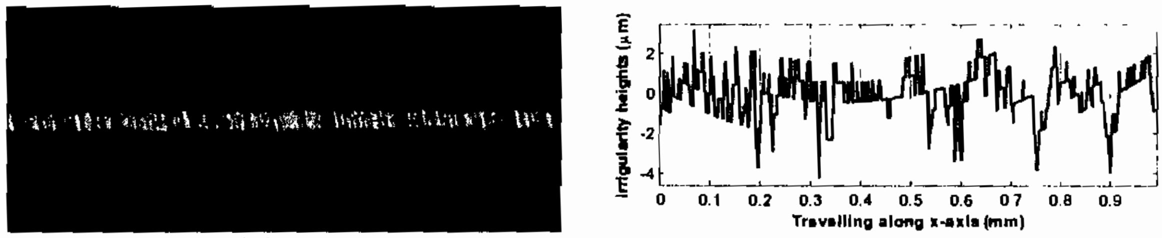
Table 4: Calculated unfiltered 3D roughness parameters of a two standard specimen surfaces

	Standard specimen I			Standard specimen II		
	SR3DVision	Mountain	Diff.%	*SR3DVision*	Mountain	Diff.%
S_a (μm)	11.26	11.2	0.54	10.43	10.4	0.29
S_q (μm)	11.97	12.00	0.25	11.06	11.10	0.36
S_{sk}	0.052	0.053	1.89	0.033	0.032	3.13
S_{ku}	1.45	1.45	0.00	1.41	1.43	1.40
S_z (μm)	44.53	42.50	4.78	38.21	36.50	4.68



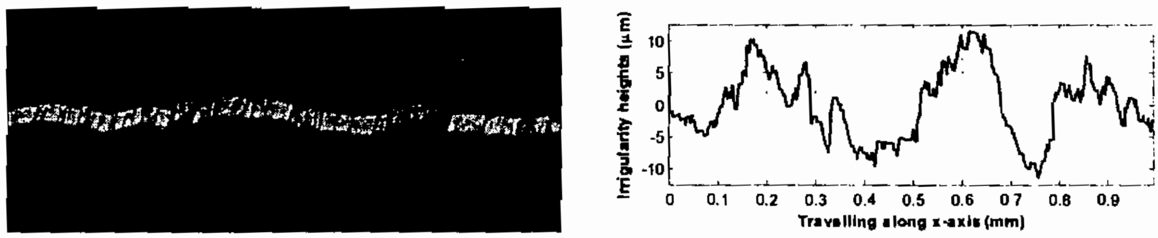
(a) Original image. (b) Roughness profile .

Fig. 10. The captured images and the final roughness profiles for turning specimen (facing).



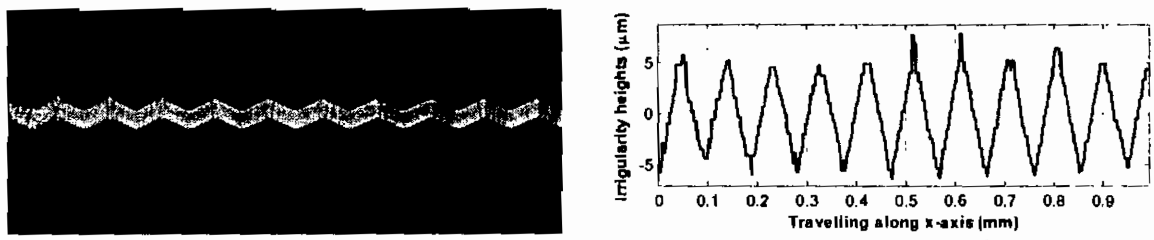
(a) Original image. (b) Roughness profile .

Fig. 11. The captured images and the final roughness profiles for ground specimen.



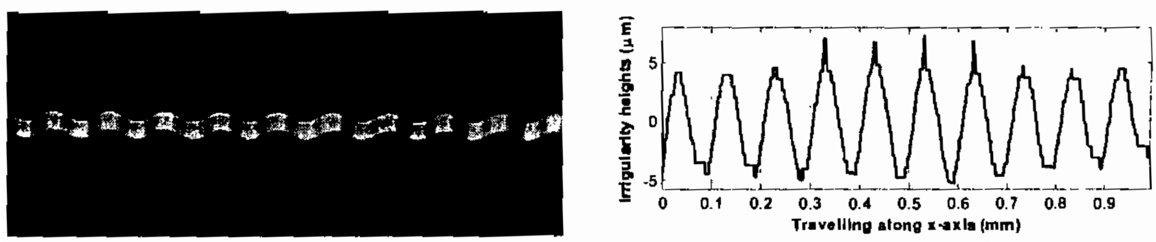
(a) Original image. (b) Roughness profile .

Fig. 12. The captured images and the final roughness profiles for milled specimen.



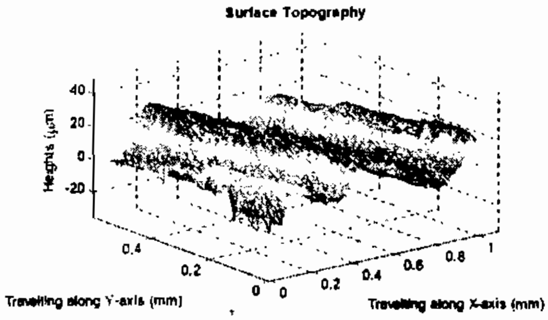
(a) Original image. (b) Roughness profile .

Fig. 13. The captured images and the final roughness profiles for standard specimen I.

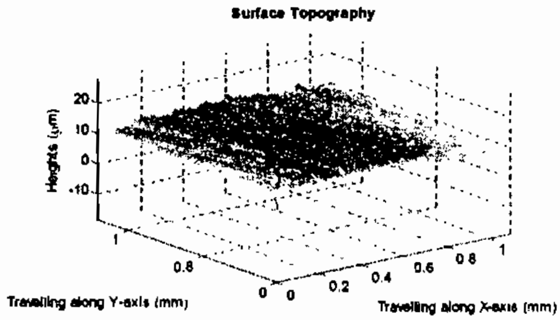


(a) Original image. (b) Roughness profile .

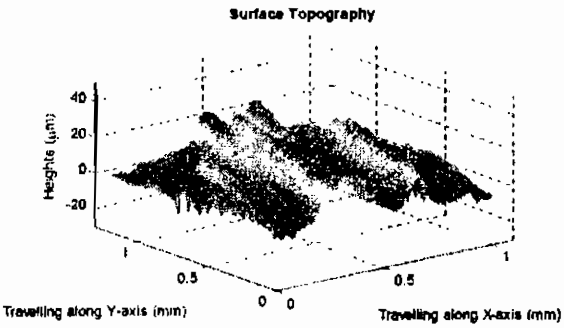
Fig. 14. The captured images and the final roughness profiles for standard specimen II.



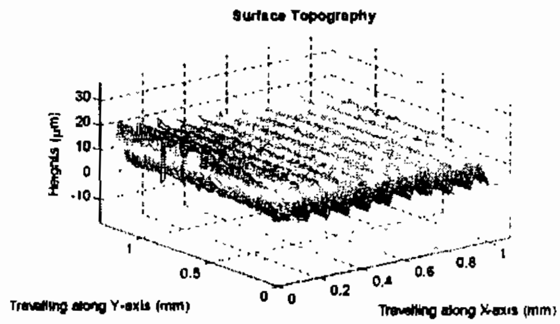
(a) Turning (facing).



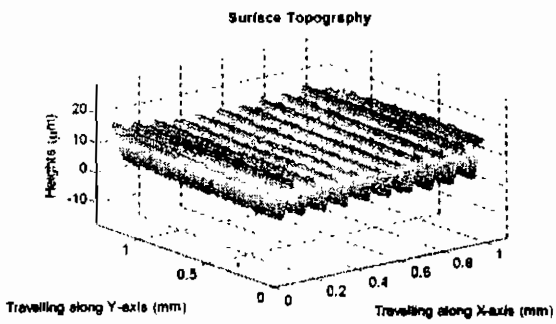
(b) Grinding.



(c) Milling.



(d) Standard specimen I.



(e) Standard specimen II.

Fig. 15. Surface topography of (a) turning (facing), (b) grinding, (c) milling, (d) standard specimen I, and (e) standard specimen II.

5 Conclusions

A non-contact and multi-parameter system for measuring surface roughness has been realized by combining a light sectioning microscope and computer vision system. The vision system has been utilized to capture images for the roughness profiles viewed by light sectioning microscope and save them for further image processing. A program named *(SRLSVision)* has been specifically written in-house to process the captured images. Four modules, supported by a graphical user interface (GUI), were developed to extract the roughness profiles from the captured images and to calculate roughness parameters from the extracted profiles. Most of the standard and non-standard surface roughness parameters are calculated by the introduced system. The system was calibrated for both horizontal and vertical resolutions, using two standard specimens, to calculate the roughness parameters in Metric units. Also, the standard specimens were used to verify the system. In addition, various samples machined by different operations were measured by the introduced system and a stylus instrument and the results showed that the maximum difference between the two systems was within ±4.8%, which prove the accuracy of the system.

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