

3D Surface Roughness Measurement Using a Light Sectioning Vision System

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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 $\pm 4.8\%$ compared with these systems.

Index Terms—3D surface roughness, Computer vision, Light sectioning.

I. 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. Many methods of measuring surface finish have been developed ranging from the simple touch comparator to sophisticated optical techniques [1]-[3]. Optical methodology [4]-[6] and computer vision systems [7]-[11] are the most common methods among the developed researches. Computer vision was implemented to measure surface roughness by many researchers [7]-[17]. 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.

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. Light sectioning methods are considered as an optical technique, which was initially proposed by Schmaltz [12] to get the roughness profile of surfaces. The use of light sectioning method combined with computer vision is suggested by many researchers [13]-[17].

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. Kiran et al. [13] 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. A design of an optical instrument for 2D surface roughness measurement was demonstrated by Shou-Bin and Hui-Fen [14]. 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 Lewandowski and Desjardins [15]. 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 [16]. Their experimental results showed a feasible method for surface roughness measurement. In a previous work [17], the author 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.

II. 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

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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.

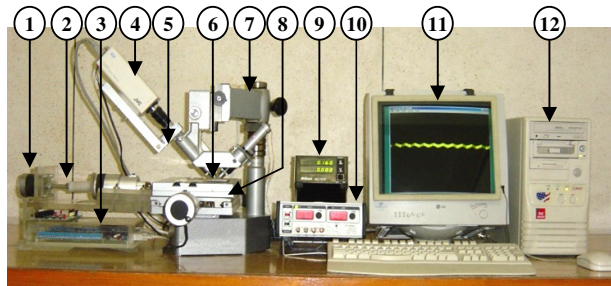


Fig. 1. Photograph of the introduced system.

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

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.

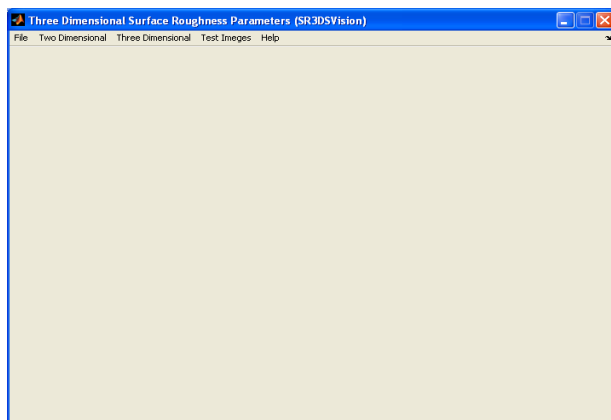


Fig. 2. Main interface of *SR3DVision* program.

The first module (*MeasControl*) is used to control the measuring process via stepper motor and its controller [18]. 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.

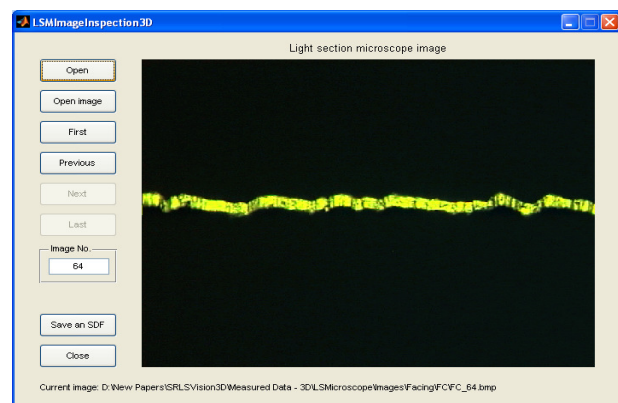


Fig. 3. Profile extraction module (*ProfileExtract*).

The third module (*RP2DCalc*), Fig. 4, is used to calculate the 2D roughness parameters [19]-[20] from the SDF file produced for each image by the second module. In addition, this module is used to view the 2D surface roughness profile extracted from each image.

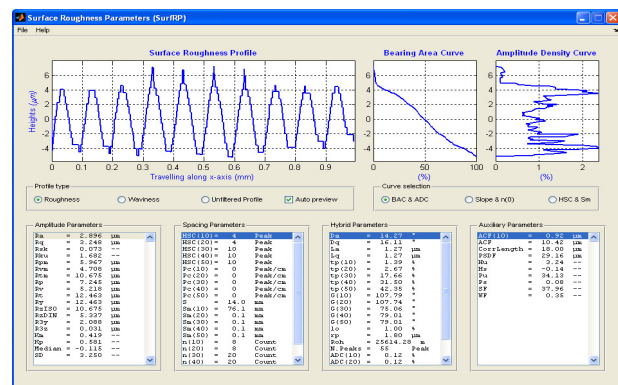


Fig. 4. Two dimensional surface roughness parameters calculation module (*RP2DCalc*).

The fourth module (*RP3DCalc*), Fig. 5, is used to calculate the 3D roughness parameters [21] 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.

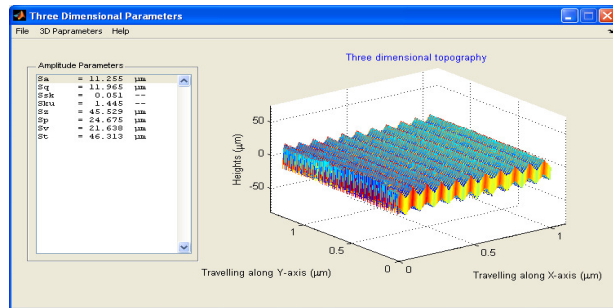


Fig. 5. Three dimensional surface roughness parameters calculation module (*RP3DCalc*).

III. 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 N_{Traces} 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.

IV. 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 V). An *SDF* file is created by the second and third modules for later use to calculate surface roughness parameters.

V. 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 I.

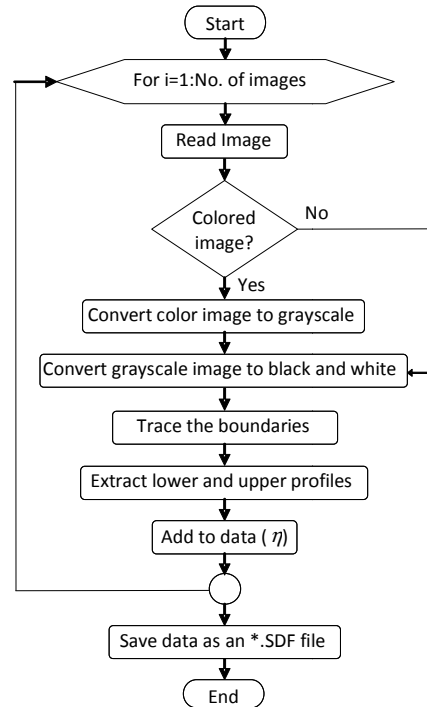


Fig. 6. Flowchart of the image processing algorithm used to extract surface heights data from the light sectioning profiles.

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 a lens of 13.9 mm focal length can be calculated as follows:

Horizontal Resolution (H)

$$= \text{Field of view/Width of the captured image} \\ = 1000/760 = 1.31579 \mu\text{m/pixel}$$

On the other hand, another standard specimen has an arithmetic average roughness $R_a = 2.97 \mu\text{m}$ and peak to valley height roughness parameter $R_t = 11.72 \mu\text{m}$ was used to calibrate the system for the vertical resolution. Fig. 7 and Table II 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)

$$= 10.95/R_t = 0.9343 \mu\text{m/pixel}$$

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

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

Lens's focal length (mm)	Horizontal field of view (mm)	Horizontal Resolution (μm/pixel)	Vertical Resolution (μm/pixel)
13.9	1.0	1.3158	0.9343

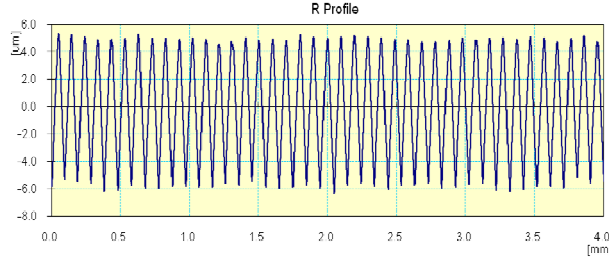


Fig. 7. Standard specimen measured by a Surftest SJ201-P.

Table II: 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

VI. 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. 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 [21].

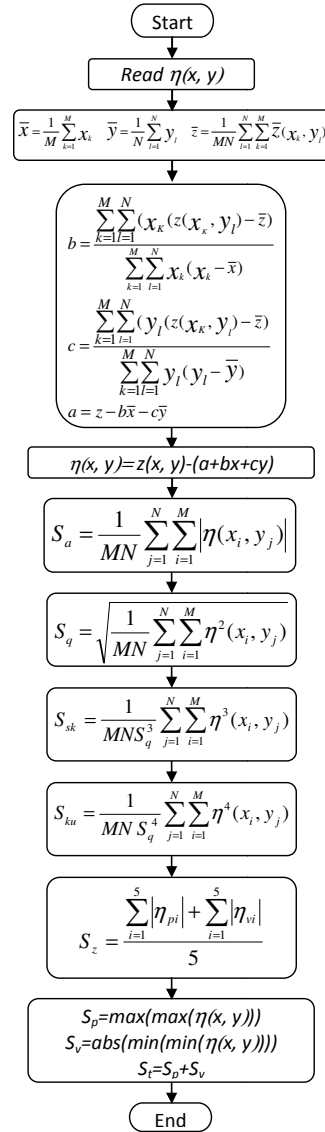


Fig. 8. Application of least square mean plane and 3D amplitude parameters calculation.

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 Peucker and Douglas [22]-[24] proposed a method to identify summits, flats, straits and ridges, the algorithm still relies on the size of neighboring area. 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.

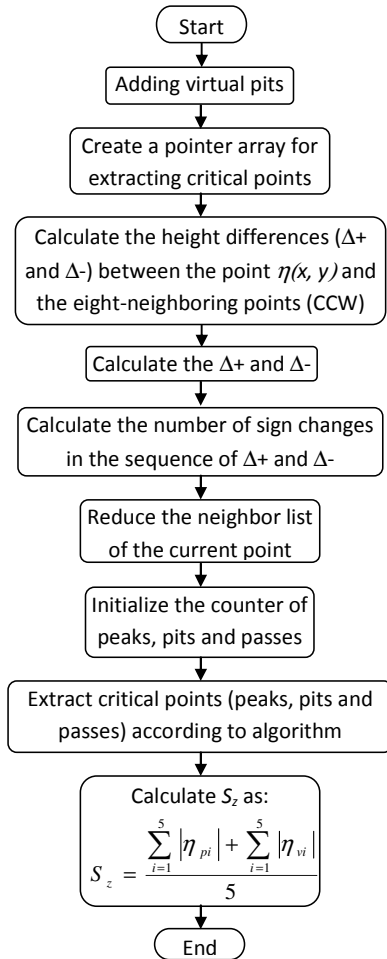


Fig. 9. Flowchart of S_z parameter calculation based on extraction of critical points (23-24).

VII. 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 *SR3D Vision* 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 as shown in Table III. The percentage of differences between the actual and the measured values were within $\pm 4.5\%$. Table IV shows the calculated three dimensional roughness parameters, obtained by both the third module of the *SR3D Vision* 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>) [25], was used to verify the *SR3D Vision* 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 6.65% 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 ranging from 0 to 3.13%. From the table, the maximum percentage of difference between the two systems does not exceed $\pm 4.8\%$.

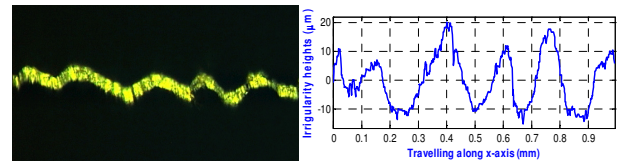
Table III: Actual and calculated roughness parameters for the two standard specimen

Standard Specimen	Average roughness 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	± 3.14
II	2.97	2.92	± 1.82	13.21	12.91	4.46	± 2.32

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

	Standard specimen I			Standard specimen II		
	<i>SR3D Vision</i>	Mountain	Diff. %	<i>SR3D Vision</i>	Mountain	Diff. %
S_a (μm)	11.26	11.2	0.54	10.43	10.4	0.29
S_q (μm)	11.97	12	0.25	11.06	11.1	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	42.5	4.78	38.21	36.5	4.68
S_p (μm)	24.68	24.8	0.48	19.66	20	1.70
S_v (μm)	21.64	22.2	2.52	19.39	19.5	0.56
S_t (μm)	46.31	47	1.47	40.05	41	2.32

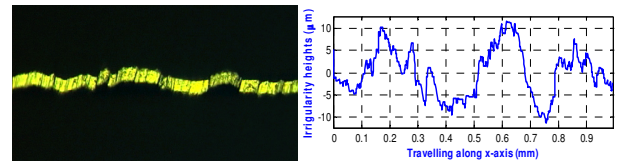
The captured images and the extracted roughness profiles for turned and a milled specimens are shown in Figs. 10 and 11, whereas, the captured images and the extracted roughness profiles for the one standard specimen is shown in Figs. 12. Fig. 13 shows the extracted surface topography of (a) turning (facing), (b) milling, and (c) standard specimen I.



(a) Original image.

(b) Roughness profile .

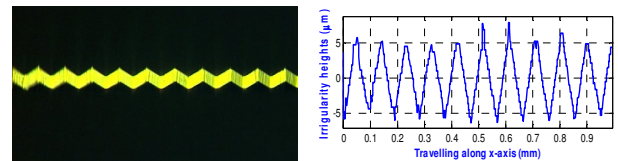
Fig. 10. The captured images and the final roughness profiles for turning specimen (facing).



(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.

VIII. 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 common 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 $\pm 4.5\%$, which prove the accuracy of the system.

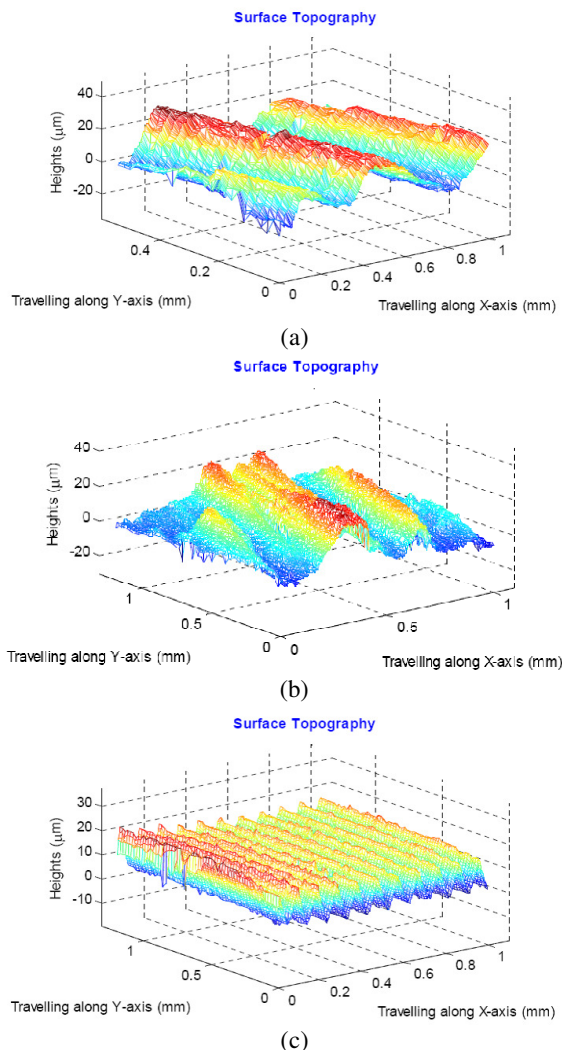


Fig. 13. Surface topography of (a) turning (facing), (b) milling, and (c) standard specimen I.

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