Surface Roughness Measurement Using Light Sectioning Method and Computer Vision Techniques

قياس خشونة الأسطح باستخدام طريقة القطاع الضوئي و أساليب الرؤية بالحاسب

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الملخص العربي:

لقد أدى التطور في الصناعات الحديثة إلى الحاجة لمنتجات صناعية ذات أسطح ناعمة للغاية، وإلى الحاجة لإمكانية قياس أسطح المنتجات الصناعية بدقة عالية، ومن هنا تزايدت أهمية قياس خشونة الأسطح الهندسية. وفي هذا البحث تم تقديم نظام جديد لقياس خشونة الأسطح باستخدام ميكروسكوب قطاع ضوئي ونظام رؤية بالحاسب. ويتميز هذا النظام بتنفيذ عملية القياس بدون تلامس. ويُستخدم ميكروسكوب القطاع الضوئي لعرض منحنى الخشونة للعينات المطلوب قياسها، ثم يستخدم نظام الرؤية بالحاسب لالتقاط صور المنحنيات المعروضة بالميكروسكوب. وقد تم استخدام برنامج (Matlab) لإنشاء برنامج تم تسميته (*SRLSVision*) خاص بتحليل الصور الملتقطة وحساب معاملات خشونة الأسطح من خلال وحدتين أساسيتين. الوحدة الأولى تُستخدم لاستخلاص منحنى الخشونة من الصور الملتقطة بتطبيق مجموعة من الخوارزميات الخاصة بتحليل الصور وأساليب الرؤية بالحاسب. وتُستخدم الوحدة الثانية لحساب معاملات الخشونة تبعا لمنظمة التوحيد القياسي العالمية (٢٢ معامل) من المنحنيات المستخلصة. وقد تم معايرة النظام لقياس الأبعاد بالنظام المتري، كما تم اختبار دقة النظام بقياس أحد العينات القياسية ومقارنة النتائج بالقيم الحقيقية للعينة. كذلك تم استخدام النظام لقياس مجموعة من العينات المشغلة بعمليات تشغيل مختلفة ومقارنة النتائج بالقيم التي تم الحصول عليها من قياس نفس العينات بأحد أجهزة المجسات. وثبت أن دقة النظام في حدود ±٥,٥% مقارنة بقراءة أجهزة المجسات.

Abstract:

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. In this work, a new approach is introduced to measure surface roughness by combining a light sectioning microscope and a computer vision system. This method has the advantage of being non-contact. The 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 the viewed profiles. A special program (named *SRLSVision*) has been totally developed in-house using Matlab™ software to analyze the captured images through two modules. The first module is used to extract the roughness profiles from the captured images by applying various image processing and computer vision algorithms. The second module is used to calculate the ISO roughness parameters (22 parameters) from the extracted profiles. The system has been calibrated for metric units and verified using a standard specimen. In addition, the system was used to measure various samples machined by different operations and the obtained results were compared with the results obtained by measuring the same samples using a stylus instrument. The accuracy of the system proved to be within ±5.5% compared with the stylus instrument readings.

Keywords: surface roughness, light sectioning, computer vision.

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1 INTRODUCTION

The functional properties of engineering surfaces are an important part of any machining process; therefore surface characterization is vital for design, manufacturing and inspection. Many methods of measuring surface finish have been developed ranging from the simple touch comparator to sophisticated optical techniques [1-3]. Optical methodology [4-10] and computer vision systems [11-17] are the most common methods among the developed researches. 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.

Light sectioning methods are considered as an optical technique, which was initially proposed by Schmaltz [18] to get the roughness profile of surfaces. Light sectioning methods have been underway for many years. For example, a design of an optical instrument for surface roughness measurement based on light sectioning method was proposed by Shou-Bin and Hui-Fen [19]. Lewandowski et al. [20] studied light sectioning of an object surface that uses the line deformation imaged by a CCD camera to compute the object profile. The measured CCD line deformation was small and led to low resolution in profile measurements; therefore an additional cylindrical lens was used to magnify only the horizontal deformation without modifying the vertical field of view. A surface roughness measurement system using a light sectioning microscope and corresponding software was developed by Shou-Bin and Hui-Fen [21]. Their experimental results showed that the method was feasible. Kiran et al. [22] dealt with the inspecting of machined surfaces and attempted to estimate the roughness of surfaces by using direct imaging approach, phase shifting and light sectioning method. They stated that the light sectioning method is fast but requires certain amount of preprocessing before estimating the roughness.

On the other hand, computer vision was implemented to measure surface roughness by many researchers. Lee et al. [11, 12] and Ho et al. [13] studied the measurement of surface roughness in the turning process using computer vision. Gupta and Raman [14] introduced a machine vision system to compute optical parameters for the characterization of surface roughness of machined surfaces during the rotation of a specimen on a lathe. They 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 computer vision technique for automated surface roughness measurements in machining processes was proposed by Abouelatta [15]. The author confirmed that the calculated roughness parameters obtained from the vision system could be used for online surface roughness measurements and quality control inspection. Gadelmawla et al. [16, 17] established a vision system for measuring surface roughness in both two and three dimensions based on the intensities (gray levels) of the captured images. They concluded that their system need to be calibrated for each type of specimens, which make it suitable for measuring surface roughness in the quantitative production lines.

2 PROBLEM DESCRIPTION

An old light sectioning microscope has been established in the metrology lab of Mansoura university, faculty of engineering, since 1966 to measure surface roughness. Its capabilities are limited to measure one roughness parameter manually, typically R_t = 1.6 : 80 µm. The aim of this work is to introduce a new non-contact system for automatic measurement of surface roughness by utilizing the light sectioning microscope and a computer vision system. Consequently, many roughness parameters, rather than R_t, can be measured by the system.

3 BACKGROUND OF THE LIGHT SECTIONING METHOD

Light sectioning microscopes are used to view profiles of surface sections by arranging both the illumination and the observation directions to form an angle α (usually 45) with the surface. The most famous method in light sectioning is that due to Schmaltz who illuminated the surface past a knife-edge [18]. The only way to get a magnified view of the surface was to project a slit or edge onto the surface at an angle α as shown in Fig. 1. The light source illuminates the slit, which by means of the objective O_1, is reproduced on the surface as a fine band of light. This band is observed through a microscope whose objective O_2 has the same magnification as objective O_1. The illumination and the observation microscope are arranged at right angles to each other. They form an angle of 45 degrees with the surface to be measured. The reticle is visible in the eyepiece, and can be adjusted to within the field of view by means of a measuring drum.

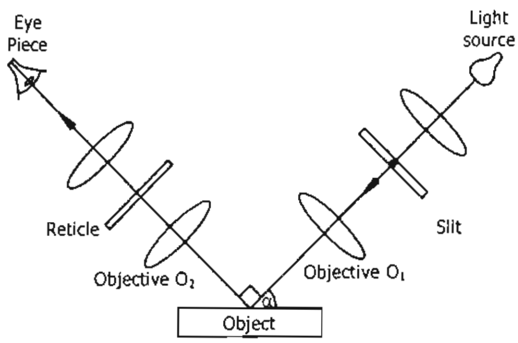


Fig. 1. Basis of the light sectioning method

4 EXPERIMENTAL SETUP

The introduced system consists of two major parts, hardware and software. A photograph of the system is shown in Fig. 2.

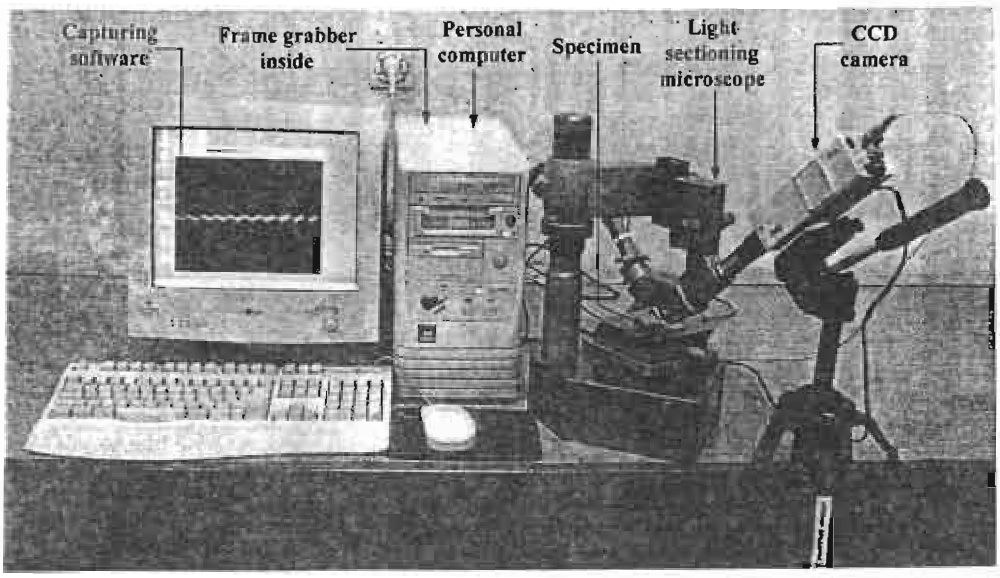


Fig. 2. Photograph of the introduced system

4.1 Hardware

The hardware consists of three main items: personal computer (PC), a light sectioning microscope and a vision system. The PC is an IBM-compatible personal computer with

Pentium processor and Windows operating system. The light sectioning microscope is supplied with four different sets of magnification lenses to produce a magnified roughness profile for surface with different grades of roughness. The vision system consists of a JVC color video camera (CCD) and an ELF-VGA frame grabber provided with a capturing software to capture the images seen by the CCD camera. The CCD camera is fixed on the eye piece of the Light sectioning microscope to view the produced roughness profiles. The frame grabber is fitted inside the PC and connected to the CCD camera, and it is used to digitize the analogue image, produced by the CCD camera, into 760x570 pixels with 16 bits of color.

4.2 Software

A special program (named *SRLSVision*) has been developed in-house, using Matlab™ software [23] and the provided image processing toolbox [24], to analyze the captured images. Two modules with Graphical User Interface (GUI) have been designed to extract the roughness profile and to calculate the surface roughness parameters from the captured images. Through the first module (Fig. 3), two inputs should be entered by the user. The first input is the captured image to be analyzed and the second input is the focal length of the lens used to capture the image. The first module 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. The extraction process is performed automatically by just clicking a button, however, most of the parameters which affect the extraction process can be controlled by the user through the designed GUI. The x-z coordinates of the extracted profile is saved to a Surface Data Format (SDF) file, which could enable straightforward interchange of topographic data between different software packages [25], for further use by the second module.The second module (Fig. 4) is used to open the SDF file and calculate the ISO roughness parameters [26].

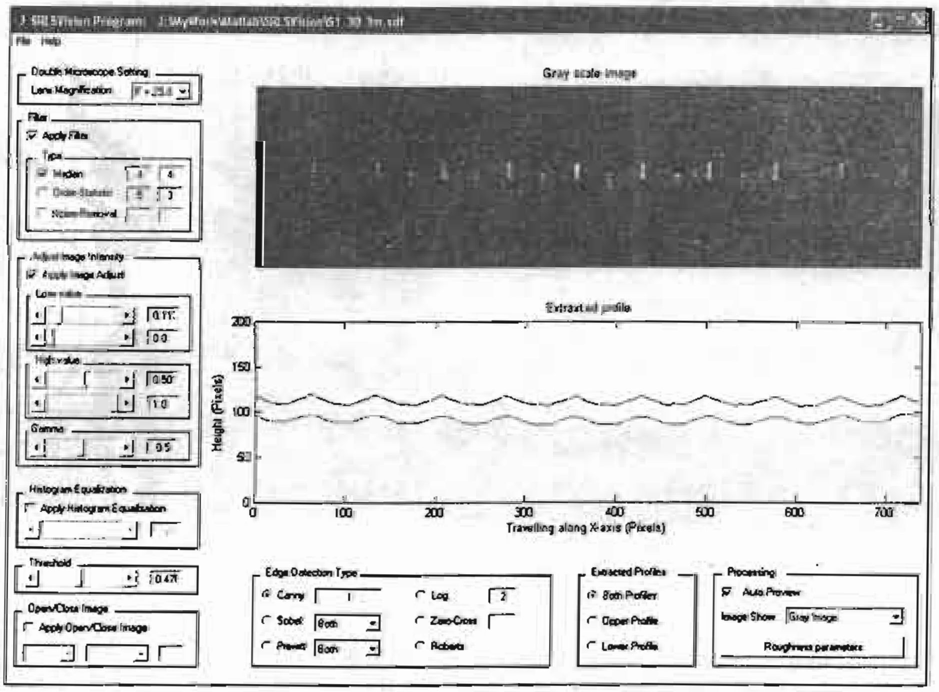


Fig. 3. Main interface of the *SRLSVision* program

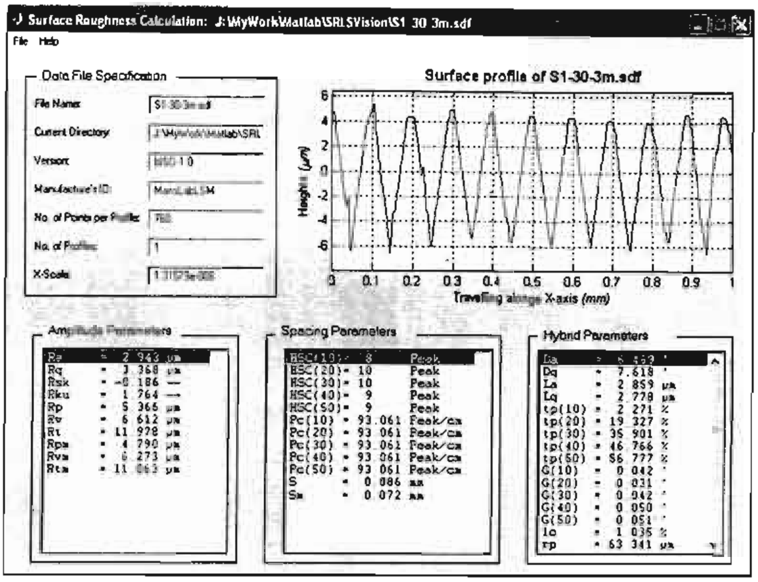


Fig. 4. Interface of the surface roughness parameters calculation module

5 PROCEDURES OF WORKING

To calculate the surface roughness parameters 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 on the screen of the capturing software (ELF-VGA). The longitudinal and cross tables of the microscope can be used to move the specimen in X and Y directions to select different sections on the surface. After selecting the required section, the capturing software is used to capture an image for the viewed profiles and save it to a bitmap image file (BMP). Finally, the captured image is opened by the *SRLSVision* program and the focal length of the lens used to capture the image is selected by the user, then the processing algorithms are applied.

In Fig. 3, the *Auto Preview* check box is used to control the automatic extraction of the roughness profiles when the processing parameters are changed by the user. If this check box is checked, the extracted profiles will be updated automatically if the user changes any of the processing parameters. Otherwise, the extracted profiles will not be updated until the user checks the *Auto Preview* check box again. The roughness parameters of the extracted profile can be calculated by clicking the *Roughness Parameters* button, which displays the second module as shown in Fig. 4.

6 PROCESSING ALGORITHMS

Many image processing and computer vision algorithms were used to analyze the captured images and to extract the roughness profiles as shown in Fig. 5. The first algorithm is used to check the depth of color in the opened image. If the image is colored, it is converted to grayscale. Next, the median filter is applied to the gray image to reduce the noise "salt and pepper" from the image. If the brightness or the contrast of the image is low, they are adjusted automatically by the software to enhance the image.

The segmentation proeess comes after the enhancement process. In this stage, a global threshold is calculated to convert the grayscale image into a binary image. The output binary image has values of 0 (black) for all pixels in the input image with luminance less than the threshold value and 1 (white) for all other pixels. The binary image is passed to the edge detection algorithm to produce an edged image, in which the edge pixels are marked by one's while non-edge pixels are marked by zero's.

The edged image is processed by a labeling algorithm, which produces a labeled matrix (of the same size as the edged image), in which each group of connected pixels are labeled with different number to produce profiles with different lengths.

After labeling, the labeled matrix is sorted and the longest two profiles are selected as the upper and lower roughness profiles, while other profiles are considered as noises. The longest two profiles are filtered by a refining algorithm, specifically written for this purpose, to remove the illogical pixels from the extracted profiles. The upper and lower profiles are differentiated by comparing the z coordinates of their pixels.

Finally, a calibration algorithm is applied on the extracted two profiles to calculate the actual x and z coordinates, then an SDF file is created and sent to the second module to calculate the roughness parameters.

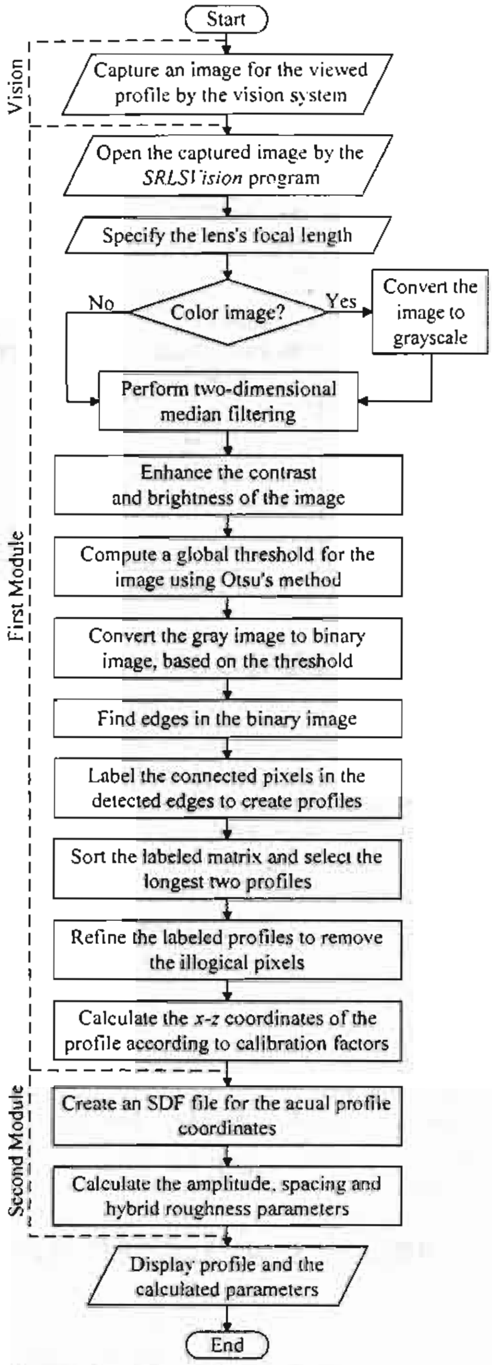


Fig. 5. Flowchart of the *SRLSVision* program

7 SYSTEM CALIBRATION

The light sectioning microscope is provided with four pairs of lenses (objectives and oculars) with different focal lengths. Each pair is suitable for measuring specific grades of surface roughness as shown in Table 1. The system has been calibrated for these lenses in both x direction (horizontal resolution) and z direction (vertical resolution). Therefore, the focal length for the lens used to capture the image under processing should be entered to the *SRLSVision* program by the user.

7.1 Calibration of the horizontal 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. Each pair of the four lenses 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. Because the implied vision system produces images sized to 760x570 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). For example, the horizontal resolution for the lens of 13.9 mm focal length ($Res_{H(13.9)}$) can be calculated as follows:

$$Res_{H(13.9)} = \text{Field of view / Width of the captured image}$$
$$= 1000\ /\ 760 = 1.31579\ \mu m/pixel$$

The horizontal resolution for other lenses was calculated and listed in Table 1.

7.2 Calibration of the vertical resolution

A standard specimen has an arithmetic average roughness R_a=2.97 μm and peak to valley height roughness parameter R_t = 10.95 μm was used to calibrate the system for the vertical resolution. Fig. 6 shows a sample roughness profile of the standard specimen (4 mm length) obtained by a Handysurf connected to a personal computer [27]. An image was captured for the standard specimen using the lens of 13.9 mm focal length, then the longest two roughness profiles were extracted by the *SRLSVision* 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 profiles. The maximum peak to valley height was calculated (in pixels) for each of the longest two profiles, then the average value was taken (13.4234 pixels in this case). The vertical resolution ($Res_{V(13.9)}$) was calculated by dividing the actual value of R_t by the calculated average as follows:

$$Res_{V(13.9)} = 10.95\ /\ 13.4234 = 0.8157\ \mu m/pixel$$

Similarly, the vertical resolution for other lenses was calculated and listed 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 Res_H (μm/pixel)	Vertical Resolution Res_V (μm/pixel)
1	25	10 - 80	2.5 - 20	1.8	1.6454	2.3684
2	13.9	6.3 - 20	1.25 - 5	1.0	0.9141	1.3158
3	8.2	3.2 - 10	0.63 - 2.5	0.6	0.5485	0.7895
4	4.3	1.6 - 3.2	0.32 - 0.63	0.3	0.2803	0.3947

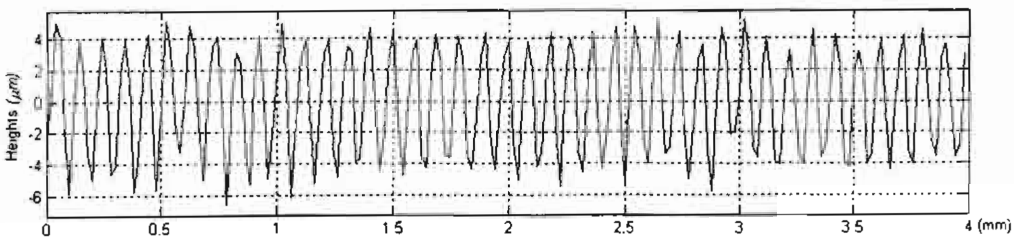


Fig. 6. The standard specimen measured by a Handysurf connected to a personal computer

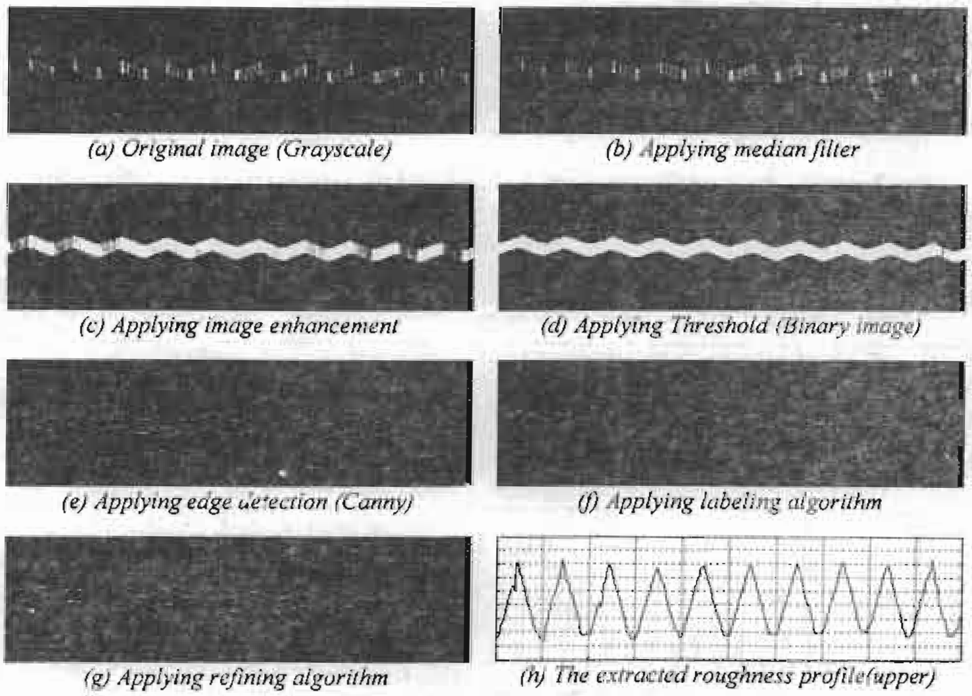
8 SYSTEM VERIFICATION

To verify the accuracy of the introduced system, five images for different sections in the standard specimen were captured and processed by the *SRLSVision* program to extract their roughness profiles and calculate the roughness parameters. The averages of R_a and R_t for the five images were calculated and compared with actual values of the standard specimen as shown in Table 2. The percentage of difference between the actual and the measured values not exceeded than ±3.5%. Table 3 shows the calculated roughness parameters, obtained by the second module of the *SRLSVision* program, for one section of the standard specimen. Figure 7 shows one of the captured images and the steps of its processing. Figure 7-a shows original image, Figs. (7-b:7-g) show the effect of the processing algorithms and Fig. 7-h shows the extracted roughness profile (upper). All processing algorithms are applied automatically by the *SRLSVision* to extract the roughness profile and calculate its roughness parameters as mentioned before.

Table 2: Actual and calculated roughness parameters for the standard specimen

Arithmetic average roughness R_a (μm)			Peak to valley height R_{tm} (μm)		
Actual	Average of 5 measurements	Difference (%)	Actual	Average of 5 measurements	Difference (%)
2.97	2.880	3.03	11.57	11.864	-2.54

The effect of some processing algorithms, specially the refining algorithm, is not clear for the standard specimen shown in Fig. 7. Therefore, another sample produced by a milling operation was processes by the introduced system and the processing results are shown in Fig. 8. The effect of the labeling and the refining algorithms can be noticed from Figs. 8-f and 8-g.



(a) Original image (Grayscale) *(b) Applying median filter*
(c) Applying image enhancement *(d) Applying Threshold (Binary image)*
(e) Applying edge detection (Canny) *(f) Applying labeling algorithm*
(g) Applying refining algorithm *(h) The extracted roughness profile(upper)*

Fig. 7 Processing algorithms for extracting the roughness profiles of the standard specimen

Table 3: Caleulated roughness parameters for the standard specimen

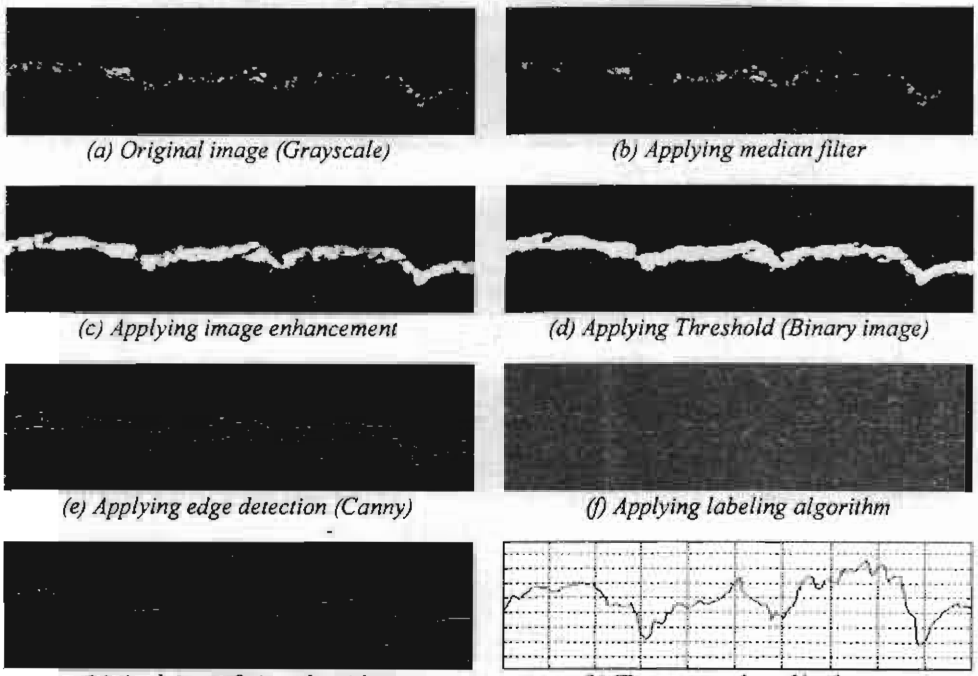
No.	Symbol	Description	Value	Units
1	R_a	Arithmetie average roughness	2.943	µm
2	R_q	Root mean square roughness	3.368	µm
3	R_{sk}	Skewness	-0.186	—
4	R_{ku}	Kurtosis	1.764	---
8	R_p	Maximum peak height	5.366	µm
9	R_v	Maximum valley depth	6.612	µm
10	R_t	Maximum peak to valley height	11.978	µm
5	R_{pm}	Mean of the maximum peak heights	4.790	µm
6	R_{vm}	Mean of the maximum valley depths	6.273	µm
7	R_{tm}	Mean of the maximum peak to valley heights	11.063	µm
11	HSC^*	High spot count	10	peaks
12	P_c^*	Peak count	93.061	peak/cm
13	S	Mean spacing of adjacent local peaks	0.086	mm
14	S_m^{**}	Mean spacing between profile peaks	0.072	mm
15	Δ_a	Average mean slope	6.469	degree
16	Δ_q	Root mean square slope	7.618	degree
17	λ_a	Average wavelength	2.859	µm
18	λ_q	Root mean square wave length	2.778	µm
19	tp^*	Bearing ratio	19.327	%
20	γ^{**}	Profile slope	0.051	degree
21	l_o	Relative length of the profile	1.035	%
22	r_p	Mean radius of asperities	63.341	µm

* Parameters calculated at 20% of the profile height
** Parameters calculated at the profile mean line

9 EXPERIMENTAL WORK

To verify the introduced system experimentally, the milled sample, discussed above, and another two different samples machined by facing turning and grinding operations were measured by both a stylus instrument (Handysurf connected to a personal computer) and the introduced system. Both the milled and the turned specimens were captured using the 13.9 mm lens, while the ground specimen was captured using the 8.2 mm lens .Each specimen was measured five times by both systems and the average values of R_a and R_t were calculated and listed in Table 4. From the table, the maximum percentage of difference between the two systems not exceeded than ±5.5%, which proves the accuracy of the introduced system.

The captured image and the final extracted roughness profile for the milled specimen is shown in Fig. 8, while the captured images and the extracted roughness profiles for the ground and turned specimens are shown in Fig. 9.



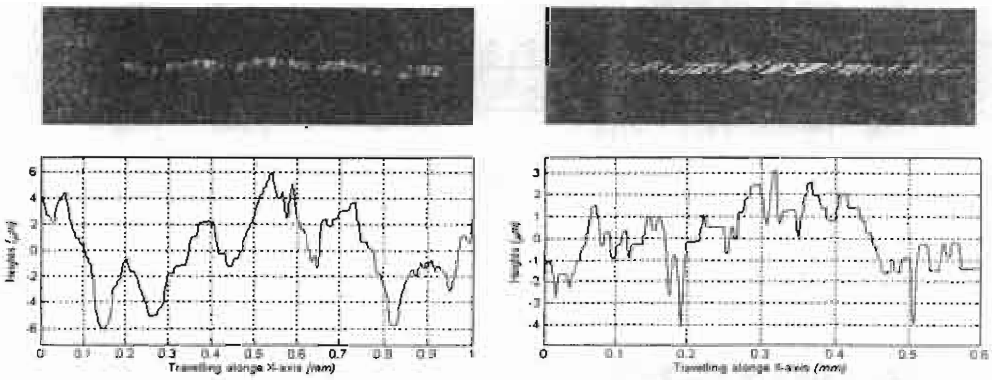
(a) Original image (Grayscale) *(b) Applying median filter*

(c) Applying image enhancement *(d) Applying Threshold (Binary image)*

(e) Applying edge detection (Canny) *(f) Applying labeling algorithm*

(g) Applying refining algorithm *(h) The extracted profile (lower)*

Fig. 8. Processing algorithms for extracting the roughness profiles of a milled specimen



(a) Facing Turning sample (upper profile) *(b) Grinding sample (upper profile)*

Fig. 9. The captured images and the final roughness profiles for turned and ground specimens

Table 4 Comparison between the results obtained from the Handysurf and the *SRLSVision* for different machining operations

system	Turning		Milling		Grinding	
	R_a	R_t	R_a	R_t	R_a	R_t
Handy Surf	2.06	12.66	3.39	27.69	0.65	6.89
SRLSVision	2.033	11.983	3.245	26.276	0.657	7.205
Difference (%)	1.31	5.35	4.28	5.11	-1.08	-4.57

10 CONCLUSION

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 processing. A program named (*SRLSVision*) has been specifically written in-house to process the captured images. Two modules supported by a graphical user interface (GUI) were developed to extract the roughness profiles from the captured images and to calculate ISO roughness parameters from the extracted profiles. Twenty two roughness parameters could be calculated by the introduced system. The system was calibrated for both horizontal and vertical resolutions, using standard specimen, to calculate the roughness parameters in Metric units. The system was verified using the standard specimen. In addition, various samples machined by different operations were measured by the introduced system and a stylus instrument and the maximum difference between the results obtained by the two systems for R_a and R_t was within ±5.5%.

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