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ORIGINAL ARTICLE

Noncontact roughness measurement of turned parts using machine vision

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Abstract The surface roughness of turned parts is usually measured using the conventional stylus type instruments. These instruments, although widely accepted, have several limitations such as low speed measurement, contacting in nature, requiring vibration-free environment, etc. Machine vision methods of roughness measurement are being developed worldwide due to their inherent advantages, including noncontact measurement, high information content, rapid measurement, and surface measurement capability. In past research, area-based light scattering method and gray scale line intensity measurement have been developed for roughness assessment using machine vision. Such methods, however, produced redundant data when applied to measure roughness of turned parts. In this paper, an alternative method of roughness measurement using the 2-D profile extracted from an edge image of the workpiece surface is proposed. Comparison with a stylus type instrument shows a maximum difference of 10% in the measurement of average roughness R_a using the vision method.

Keywords Roughness measurement · Machine vision · Turned parts

1 Introduction

Turning is a major machining operation in the metal-working and manufacturing industry. High-speed and high-volume production demands the use of fully automated machines capable of high precision machining. A major impediment to unattended precision machining is, however, tool wear. Tool wear is well-known to have a direct and significant effect on the quality of the finished product. Therefore, significant works have been carried out world-wide over the last three decades to study the effect of tool wear on the surface quality of the turned parts.

A popular method of surface quality assessment is by roughness measurement. Roughness can be measured by two main methods: contact and noncontact methods. Contact method uses a stylus that is drawn across the surface being measured. The surface undulations are picked up by an electronic transducer, usually a linear variable differential transformer that computes the surface roughness parameters, such as average roughness R_a, root mean square roughness R_q, maximum peak-to-valley height R_t, etc. Noncontact methods can be subdivided into several types depending on the method of lighting and image analysis used. These include laser scattering, optical sectioning, and area illumination methods.

In spite of the recent development of 3-D surface measurement technology, roughness of turned parts is still being measured by many researchers using the conventional stylus-type instruments first developed in the 1940s [1–5]. The main reason for the wide use of stylus methods can be attributed to the existence of traceable standards, such as ISO 4288 (1996) and BS 1134-2 (1990), against which the measurements are made [6, 7]. The main limitations of stylus type devices are (a) repeated use of the device can cause wear of the stylus tip, thus affecting the readings, (b) the workpiece usually needs to be removed from the machine for inspection, (c) careful mounting of the workpiece and the stylus head are required, (d) a vibration-free setup is required, (e) the workpiece surface

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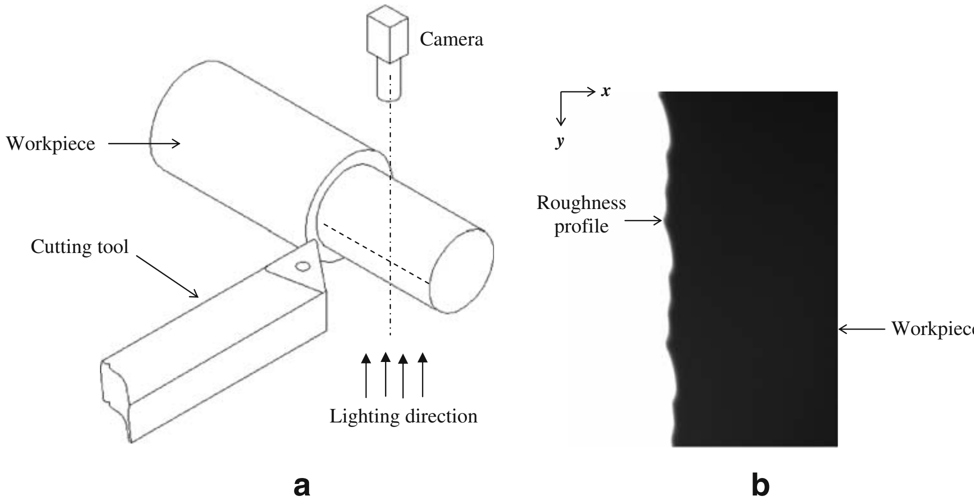


Fig. 1 **a** Schematic diagram of turning operation showing image capture direction and **b** roughness profile captured

may be scratched by the stylus needle, and (f) the measurement is slow due to the need to traverse the surface.

Noncontact roughness measurement methods usually employ a suitable lighting technique to illuminate the workpiece and a camera to acquire an image of the object from which roughness data are inferred. They have several advantages compared to the stylus methods, such as the ability for in-process or in-cycle implementation, rapid measurement capability, no parts that wear due to the noncontact nature, and the ability to provide information over a surface area. Thus, noncontacting vision-based methods are attracting significant attention from

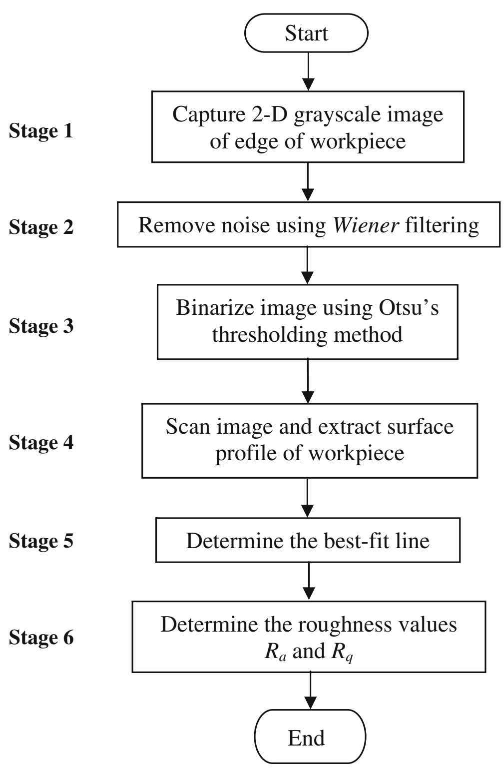


Fig. 2 Flowchart of roughness measurement algorithm

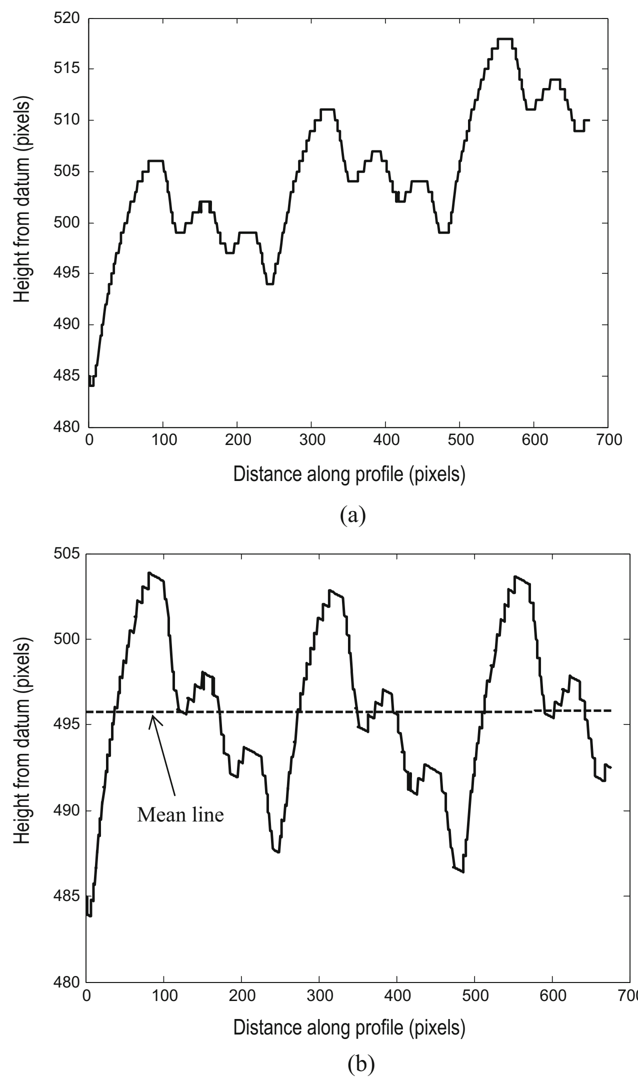


Fig. 3 Extracted roughness profile: **a** raw data **b** after fitting and subtraction

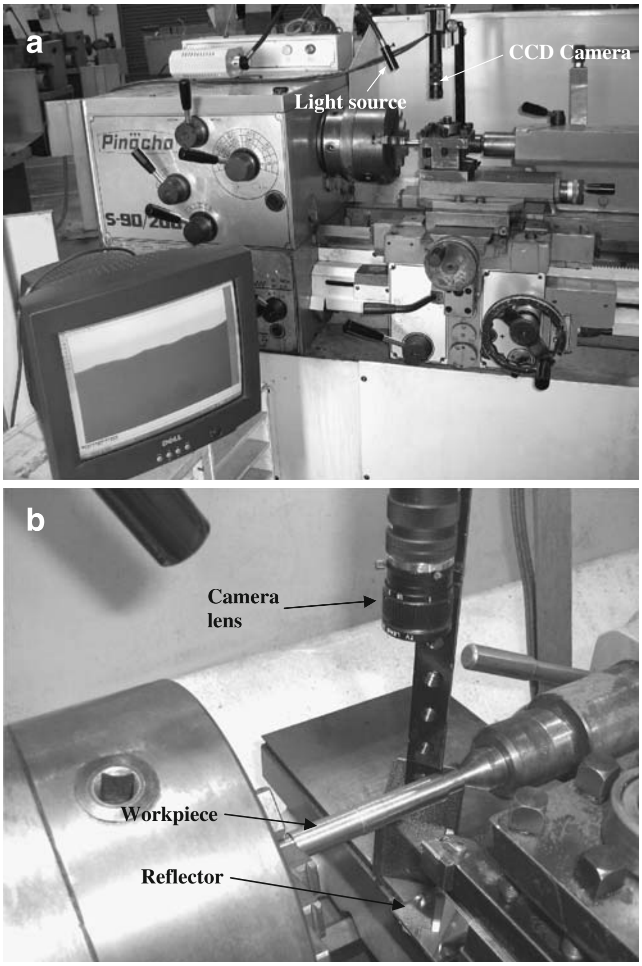


Fig. 4 **a** Hardware setup for roughness measurement and **b** close-up view of workpiece and camera

the research community [8–15]. Several commercial systems for surface measurement are currently available, such as the Wyko Series Interferometers [16], Alicona InfiniteFocus System [17], Xyris 2000 TL Surface Profiler [18], etc. Vorburger et al. [19] provided an interesting comparison in the performance between modern optical roughness measurement methods, namely confocal microscope, phase-shifting interferometer, while-light interferometer and the conventional stylus methods for a wide range of roughness values. The findings of Vorburger to a certain degree agree with the description of Whitehouse [20] when comparing the two methods for ordinary engineering surfaces.

Since the surface profile of a turned workpiece is essentially axisymmetrical, a line profile along the workpiece is usually sufficient for roughness assessment. Thus, vision and other noncontact techniques that use data extracted from an area on the part usually provide redundant information and therefore are not necessary for such application. Lee et al. [8], for instance, applied Fourier transform to an areal (2-D) image of the turned part and extracted the major peak frequency and principle component magnitude squared. These data were used as the input data in an abductive network. The computer vision-based method of surface roughness inspection of turned parts proposed by Lee and Tarng [9] uses a surface image of the workpiece from which variation of pixel gray values along a line are extracted. From the gray values, an average value is computed and used together with other machining parameters, namely cutting speed, feed, depth of cut, and a polynomial network to predict the surface roughness. The main limitation of this method is that the actual workpiece is required to predict the roughness value. A similar method was used by Lee et al. [10]. Shinn-Ying et al. [11] also used surface images and calculated the arithmetic average of the gray values along a profile for a turned part.

In this paper, an alternative method of measuring the surface roughness of turned parts using 2-D profiles of the edge of workpiece is proposed. The measurements made using this method are comparable with those obtained using the conventional stylus type method.

Fig. 5 Images of Ronchi ruling

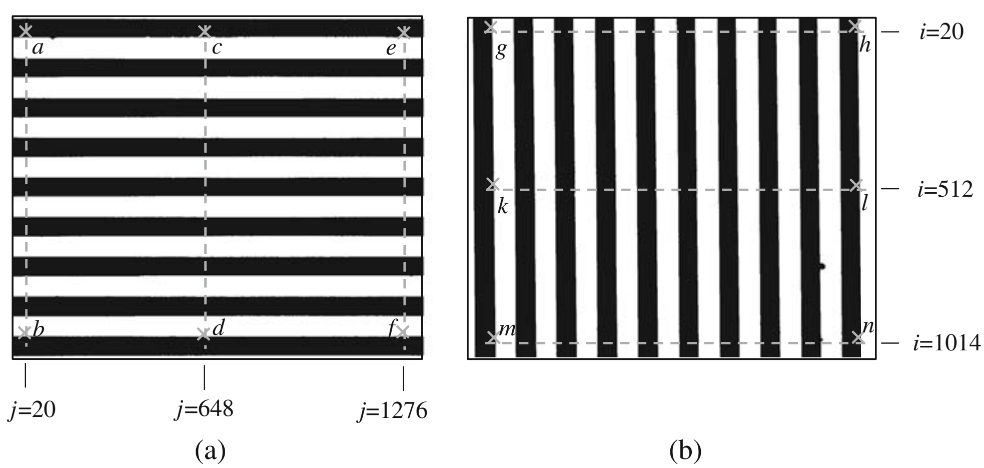


Table 1 Distances between measurement points on image (pixels)

Points	Distance (pixels)
a–b	898
c–d	899
e–f	898
g–h	1,097
k–l	1,098
m–n	1,096

2 Measurement algorithm

Figure 1a shows a schematic diagram of a typical turning operation in which an image of the workpiece is recorded from the overhead direction as shown. By positioning the camera such that the edge of the workpiece is visible, an image such as that shown in Fig. 1b can be captured. The workpiece area appears dark due to the backlighting used. Backlighting is the ideal type of illumination for such application because only a contour of the workpiece surface is needed for roughness evaluation.

Figure 2 shows the various stages of roughness measurement algorithm. In stage 1, a CCD camera that is interfaced to a computer fitted with a frame grabber was used to capture a 2-D image of the roughness profile. Noise in the image was removed using *Wiener* filtering (mask size 5×5) in the second stage. The Wiener filtering method is relatively insensitive to reverse filter of noise and is known to be one of the best filter to recover the images. In stage 3, the image was binarized to segment it into two regions, i.e., workpiece and the background. Binarization changes the original 8-bit gray scale image into a 2-bit binary image and was carried out automatically using the well-known Otsu's thresholding method [21]. The Otsu's method is the default thresholding method provided in Matlab and was sufficient for the current application due to the uniform illumination over the small field of view.

In stage 4, the contour of surface roughness profile was detected using an algorithm written in Matlab. Each image was originally saved as a 2-D matrix (X rows and Y columns). The binary image obtained from stage 3 is made up of white pixels (bit value 1) for the background and black pixels (bit value 0) for the workpiece surface. The algorithm scans the first row to locate the first black pixel on the profile. Then, it searches the second row to find the second black pixel. This procedure is repeated to detect all the black pixels that lie on the profile. These pixels reveal the contour of surface roughness of specimen as shown in Fig. 3a. In stage 5, a best-fit (mean) line of the contour data is determined using least-squares fitting. Any tilt present in the workpiece is removed by subtracting each point on detected profile from the mean value, i.e., the best-fit line (Fig. 3b). The distance of each pixel on the profile measured from the mean line is used in evaluating the average and root mean square roughness values.

In stage 6, two roughness parameters, i.e., average roughness R_a and root mean square roughness R_q were determined from the profile data. The roughness values are given by

$$R_a = \frac{f}{n}\sum_{i=1}^{n} h_i \qquad (1)$$

$$R_q = f\sqrt{\frac{\sum_{i=1}^{n} h_i^2}{n}} \qquad (2)$$

where h_i is the absolute distance of the ith point on the profile measure from the mean line, n is the number of data points, and f is a scaling factor. Since every pixel along the contour is used in the roughness calculation, the value of n is equal to the length (in pixels) of the image along the workpiece. The scaling factor f is used to change the pixel values to micrometers and was determined by calibration as explained in the next section.

3 Experimental setup

Figure 4a, b shows the actual hardware setup. The vision system comprises a high-resolution (1,296×1,024 pixels)

Table 2 Machining parameters

Machine tool	Conventional lathe Pinocho S90-200
Workpiece	Alloy steel rod AISI 304
Cutting tool	Uncoated cemented carbide: TPUN-16-03-04_H13A Sandvik Co. Ltd, Sweden
Feed rate	0.2, 0.25, 0.3, 0.4 mm/rev
Machining depth	0.25 mm
Cutting speed	25.5, 37.7, 56.5 m/min
Coolant	Air
Machining duration	0 (unworn cutting tool)

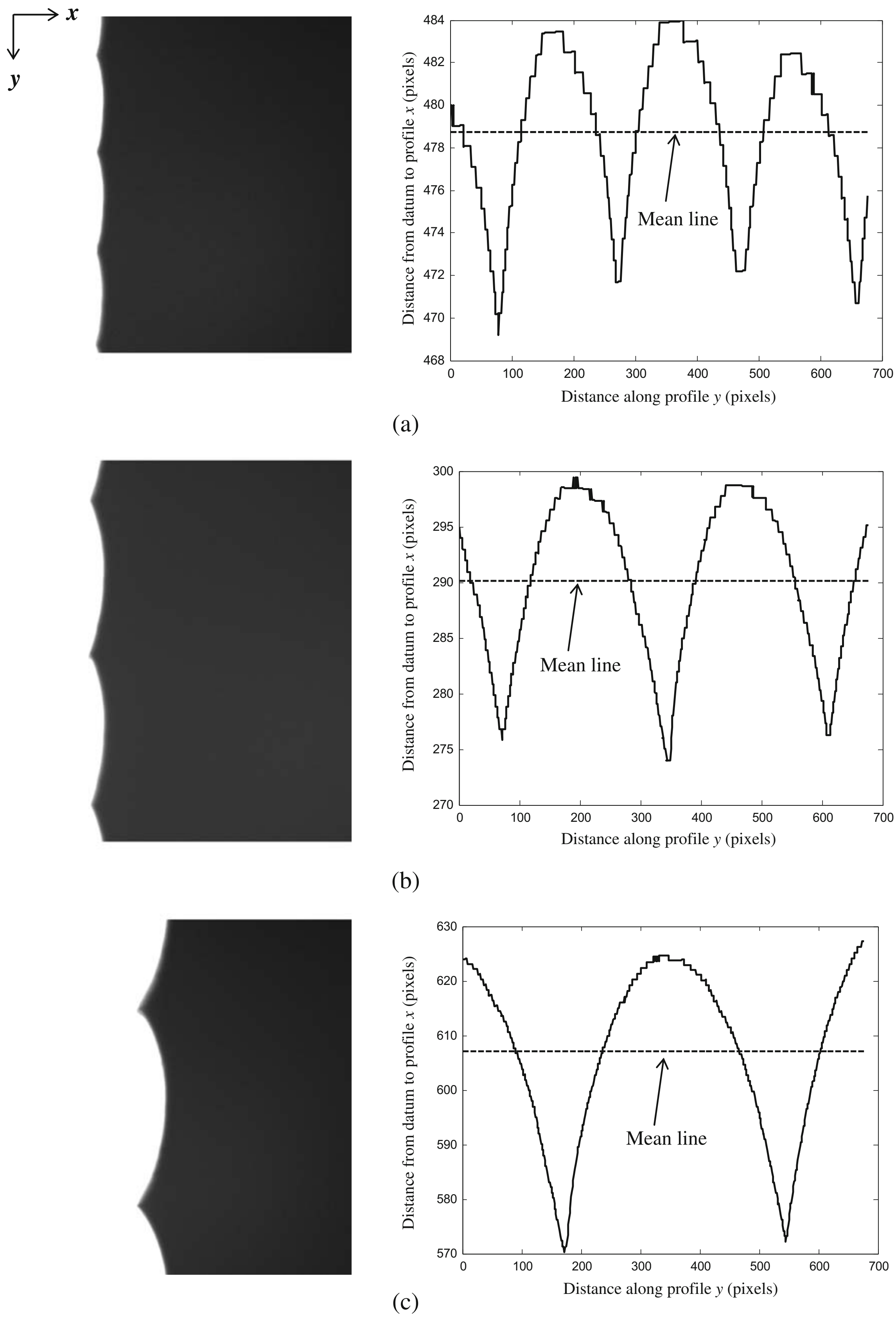


Fig. 6 Workpiece profiles and extracted roughness profiles for various feed rates: **a** 0.2, **b** 0.3, and **c** 0.4 mm/rev

CCD camera (JAI CV-A1, Japan), a 25-mm lens (model GMHR32514MCN, Goyo Optical Inc., Japan) fitted with a 110-mm-long extension tube, a frame grabber (Data Translation DT3162), and a Pentium 4 (520 MB, 2 GHz) computer. Illumination was obtained using a fiber-optic light source (TS38-583, Edmond Optics) that uses a 30-W focused quartz halogen lamp. The focused halogen lamp produces a diffused uniform illumination over a small area. Unlike directional lighting, precise adjustment of the incident angle is not necessary because a uniform background illumination that produced high quality images could be obtained due to the small field of view (1.3×1.1 mm) of the camera. A reflector placed below the workpiece deflected the light toward the camera, thus creating a silhouette of the workpiece. The intensity of the light source and the lens aperture were adjusted to avoid burnout in the image. The focusing ring of the camera was adjusted so that the edge of the workpiece is sharply in focus. It is important to align the camera with the workpiece so that image of the workpiece edge appears approximately vertical relative to the image frame.

Since the use of a long extension tube can lead to image distortion, a high-precision Ronchi rulings (200 lines/mm; Edmond Optics Inc.) was used to investigate the severity of distortion in the image. The rulings were placed in orthogonal directions in the object plane and separate images were captured (Fig. 5a, b). The distance between selected points were determined directly from the image and are shown in Table 1. The maximum difference in the distances between the points is 2 pixels (0.18%), thus assuring that the distortion is negligible. The horizontal and vertical scaling factors required to convert pixels to micrometers were determined using a standard Mitotuyo pin gage (0.8 mm). The pin gage was positioned at the same level as the axis of the workpiece so that the scaling factors are determined at a position that corresponds to the location of the workpiece edge. The horizontal and vertical scaling factors were found to be 1.00 and 1.06 μm/pixel, respectively. The field of view was 1.3×1.1 mm.

To study the effectiveness of the proposed surface roughness measurement method, AISI 304 alloy steel rods were machined using uncoated carbide inserts. Table 2 shows the machining conditions used. Four different feed rates and three different cutting speeds were used to shape 12 surface roughness profiles. The depth of cut was fixed at 0.25 mm so that the workpiece surface is mainly formed by the tool nose area. Sixteen images of the workpiece surface were captured at various locations along the edge using the vision system. Each image was scanned to extract the roughness profile. The average values of R_a and R_q for the 16 images were calculated from the profiles using Eqs. 1 and 2. This was repeated for the 12 workpieces shaped under different cutting speeds and feed rates. Figure 6 shows samples of workpiece images and the extracted profiles for three different feed rates. The workpieces were machined using an unworn cutting tool. A graphical user interface (GUI) developed in Matlab was used to determine the roughness parameters (Fig. 7).

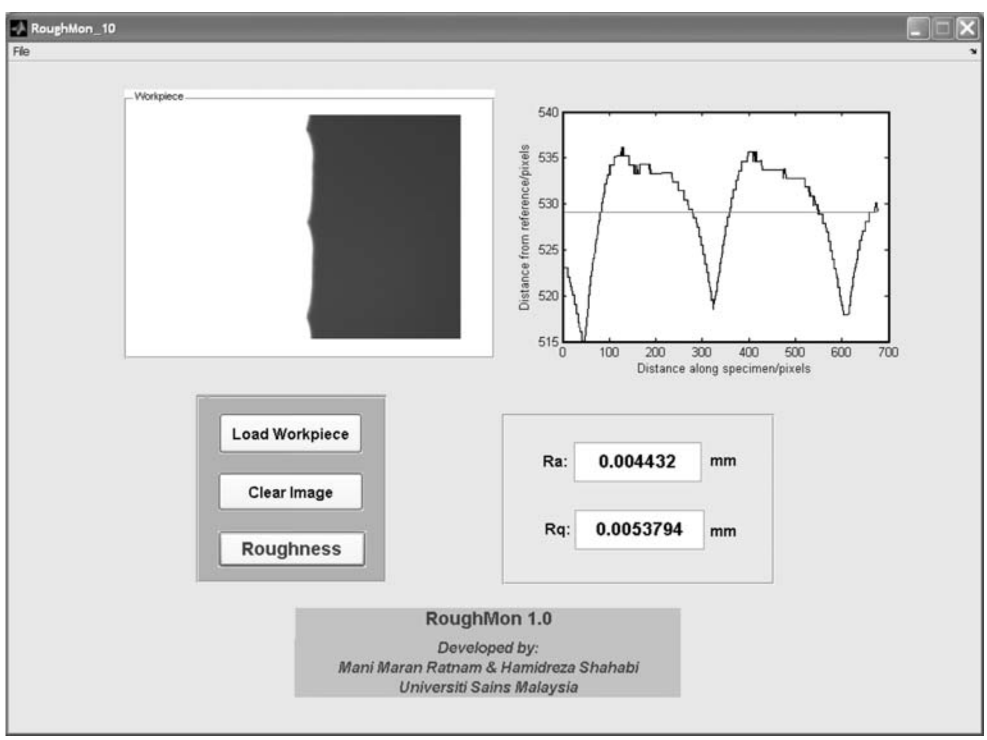


Fig. 7 GUI for roughness measurement

Table 3 Maximum and minimum R_a and R_q obtained using stylus method

Cutting speed (m/min)	Feed rate (mm/rev)	$R_{a\ max}$ (μm)	$R_{a\ min}$ (μm)	ΔR_a (μm)	ΔR_a (%)	$R_{q\ max}$ (μm)	$R_{q\ min}$ (μm)	ΔR_q (μm)	ΔR_q (%)
25.5	0.2	1.92	1.71	0.21	12.3	2.26	1.98	0.28	14.1
	0.25	2.72	2.53	0.19	7.5	3.07	2.91	0.16	5.4
	0.3	3.39	3.21	0.18	5.6	3.96	3.62	0.34	9.4
	0.4	5.18	4.89	0.29	5.9	6.22	5.9	0.32	5.4
37.7	0.2	1.89	1.72	0.17	9.9	2.16	1.97	0.19	9.6
	0.25	2.78	2.63	0.15	5.7	3.27	2.98	0.29	9.7
	0.3	3.59	3.38	0.21	6.2	4.25	3.92	0.33	8.4
	0.4	6.95	6.43	0.52	8.1	8.11	7.48	0.63	8.4
56.5	0.2	1.99	1.66	0.33	19.9	2.38	1.97	0.41	20.8
	0.25	2.88	2.50	0.38	15.2	3.34	3.01	0.33	10.9
	0.3	2.69	2.55	0.14	5.5	3.21	3.05	0.16	5.2
	0.4	6.60	6.25	0.35	5.6	7.75	7.49	0.26	3.5
Mean of differences				0.26	8.9	–	–	0.31	9.3

$\Delta R_a = R_{a\max} - R_{a\min}$, $\Delta R_q = R_{q\max} - R_{q\min}$, $\Delta R_a(\%) = \frac{R_{a\max}-R_{a\min}}{R_{a\min}} \times 100$, $\Delta R_q(\%) = \frac{R_{q\max}-R_{q\min}}{R_{q\min}} \times 100$

4 Results and discussion

4.1 Roughness measured using stylus method

A stylus type roughness tester (Mitutoyo model SJ-201P) was used to compare the results of roughness measured using the vision system. Each surface was measured 16 times at various positions of the workpiece using a cutoff of 0.8 mm. The cutoff was selected to include the maximum feed spacing of 0.4 mm/rev. The maximum and minimum values of surface roughness (R_{amax}, R_{amin}, R_{qmax}, R_{amin}) obtained using the stylus method for the 16 measurements are shown in Table 3. The deviation ΔR_a between the maximum and minimum values of R_a for the 12 specimens varied between 0.14 and 0.52 μm. The maximum deviation as a percentage of the minimum value of R_a for each workpiece is 19.9%. For R_q, the maximum deviation ΔR_q is 20.8% of the minimum value of R_q. The results obtained using the stylus instrument show that the surface roughness values at different points of the same workpiece may deviate up to 20%. This deviation could be due to the instability of the machining process carried out on a

Table 4 Maximum and minimum R_a and R_q obtained using vision method

Cutting speed (m/min)	Feed rate (mm/rev)	$R_{a\ max}$ (μm)	$R_{a\ min}$ (μm)	ΔR_a (μm)	ΔR_a (%)	$R_{q\ max}$ (μm)	$R_{q\ min}$ (μm)	ΔR_q (μm)	ΔR_q (%)
25.5	0.2	2.04	1.65	0.39	19.1	2.44	1.93	0.51	20.9
	0.25	2.61	2.2	0.41	15.7	2.98	2.47	0.5	16.8
	0.3	3.63	2.9	0.73	20.1	4.3	3.38	0.92	21.4
	0.4	5.79	4.57	0.94	16.2	6.71	5.63	0.9	13.4
37.7	0.2	1.83	1.6	0.23	12.6	2.14	1.86	0.29	13.6
	0.25	3.17	2.69	0.42	13.2	3.51	2.98	0.5	14.2
	0.3	3.78	3.15	0.63	16.7	4.37	3.69	0.68	15.5
	0.4	7.52	6.21	0.84	11.2	8.71	7.22	0.95	10.9
56.5	0.2	1.99	1.56	0.43	21.6	2.29	1.85	0.44	19.3
	0.25	2.81	2.44	0.37	13.2	3.28	2.83	0.45	13.7
	0.3	3	2.37	0.63	21	3.56	2.78	0.78	21.9
	0.4	7.07	5.64	1.44	20.4	8.49	6.65	1.84	21.6
Mean of differences				0.62	16.7	–	–	0.73	16.93

$\Delta R_a = R_{a\max} - R_{a\min}$, $\Delta R_q = R_{q\max} - R_{q\min}$, $\Delta R_a(\%) = \frac{R_{a\max}-R_{a\min}}{R_{a\max}} \times 100$, $\Delta R_q(\%) = \frac{R_{q\max}-R_{q\min}}{R_{q\max}} \times 100$

$R_{a\ min}$, $R_{a\ max}$ the minimum and maximum R_a measured using vision method; $R_{q\ min}$, $R_{q\ max}$ the minimum and maximum R_q measured using vision method

Table 5 Comparison between roughness determined using vision method and stylus method

Cutting speed (m/min)	Feed rate (mm/rev)	$R_{a\ (v)}$ (μm)	$R_{a\ (s)}$ (μm)	$\frac{\lvert R_{a(s)}-R_{a(v)}\rvert}{R_{a(s)}}$ (×100%)	$R_{q\ (v)}$ (μm)	$R_{q\ (s)}$ (μm)	$\frac{\lvert R_{q(s)}-R_{q(v)}\rvert}{R_{q(s)}}$ (×100%)
25.5	0.2	1.81	1.75	3.4	2.14	2.10	1.9
	0.25	2.50	2.62	4.6	2.87	3.03	5.3
	0.3	3.25	3.23	0.6	3.73	3.77	1.1
	0.4	5.23	4.95	5.7	6.28	6.04	4.0
37.7	0.2	1.72	1.76	2.3	2.00	2.18	8.3
	0.25	2.96	2.69	10.0	3.41	3.13	9.0
	0.3	3.38	3.49	3.2	3.97	4.10	3.2
	0.4	6.82	6.70	1.8	8.02	7.78	3.1
56.5	0.2	1.74	1.76	1.1	2.06	2.18	5.5
	0.25	2.58	2.67	3.4	3.06	3.23	5.3
	0.3	2.61	2.64	1.1	3.11	3.15	1.3
	0.4	6.48	6.42	0.9	7.66	7.63	0.4
Mean difference				3.2	–	–	4.0

$R_{a\ (v)}$, $R_{q\ (v)}$ average and root mean square roughness determined using vision method; $R_{a\ (s)}$, $R_{q\ (s)}$ average and root mean square roughness measured using stylus method

conventional lathe machine. However, the mean deviation of 8.9% between the maximum and minimum values of R_a among the 12 workpieces shows that the roughness measured using the stylus method could be compared to those measured using the proposed vision method with reasonable degree of accuracy.

4.2 Comparison between stylus method and vision method

Table 4 shows the minimum, maximum, and deviation in roughness values for the 16 images determined by the vision method for each workpiece. The measurements by vision method also show deviations comparable to those obtained by the stylus method, i.e., up to 21.6%. Table 5 shows the results of surface roughness measurement using the proposed machine vision method and the comparison with the mechanical stylus method. The results show that the maximum differences in R_a and R_q between the two methods are, respectively, 10% and 9%. The mean and the standard deviation of the difference between the two measurements for R_a are 3.2% and 2.7%, respectively. Also, the mean and the standard deviation of the difference for R_q are 4% and 2.8%, respectively. Figure 8 shows a plot of average roughness determined using the proposed vision method ($R_{a(v)}$) against the average roughness determined from the stylus measurement ($R_{a(s)}$). The data were fitted with a linear trend line and the correlation value was determined using linear regression in Microsoft Excel. A correlation value of one would indicate a perfectly linear relationship between the two sets of data. For the measurement obtained in this study, the high correlation of 0.9952 shows that the vision method is capable of providing reliable roughness values.

4.3 Effect of ambient light on roughness measured using vision method

To study the effect of ambient light on the roughness measured using the vision method, 16 images of one region of a workpiece (feed rate of 0.2 mm and other machining condition are given in Table 2) were captured under different ambient light intensities. A light meter (Lx-101A, LT Lutron) was used to record the ambient light

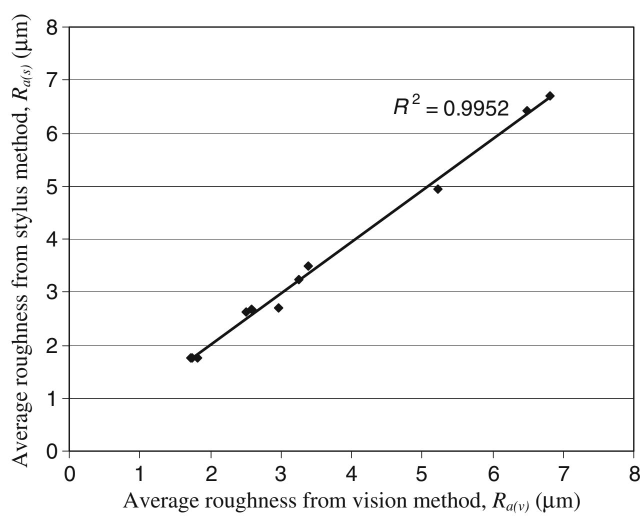
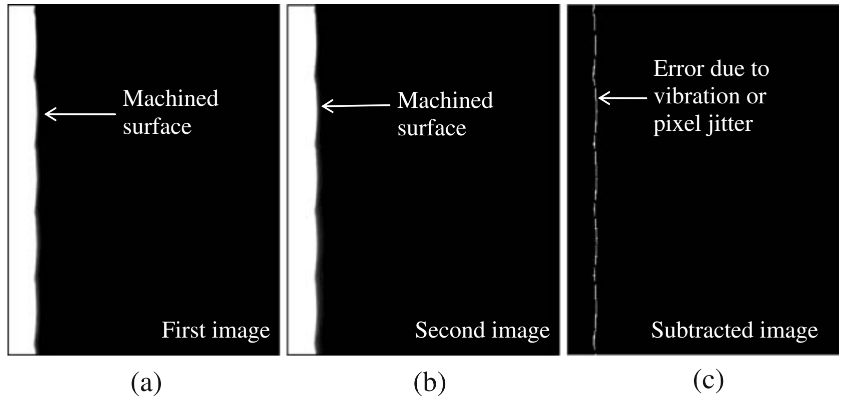


Fig. 8 Comparison between roughness determined using vision method and stylus method

Fig. 9 Images of surface roughness profile in the presence of ambient vibration: **a** first image, **b** second image, and **c** subtraction of images in **a** and **b**



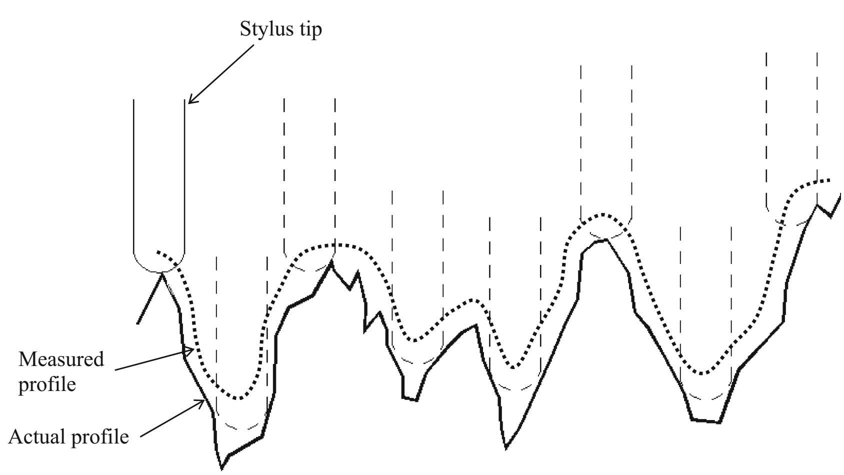
intensity. The light intensity was varied between 12 and 1,935 lux. The surface roughness values of all 16 profiles were determined using the algorithm developed. The mean values of R_a and R_q for 16 images due to the different light intensities were found to be 1.81 and 2.20 µm. The maximum deviation in R_a and R_q between the 16 roughness measurements were 2.1% and 2.2%, respectively, with respect to the minimum value. The small deviations show that the measurement accuracy is not seriously affected by ambient light variation. This result can be expected because under backlighting condition, the effect of ambient lighting is merely to alter the low intensity in the workpiece region. Using the automatic thresholding method, the effect of ambient light variation can be effectively nullified.

4.4 Effect of vibration on roughness measured using vision method

The presence of vibration is a serious problem in roughness measurement using stylus type instruments. To study the effect of vibration in the environment on the measured roughness using the vision system, 16 different images of one region of a workpiece were captured under the same lighting condition. Since neither the workpiece nor the camera was moved during the capture, any difference between the images could be attributed to vibration, system instability, changes caused by thermal effects, or pixel jitter in the image. Since the experiment was carried out under room temperature conditions, the difference, if any, is most probably due to vibration or pixel jitter. Figure 9a, b shows two sample images of the workpiece profiles recorded after a brief delay and Fig. 9c is the result of subtracting these images pixel by pixel. The white pixels in the figure after subtraction show the combined effect of vibration and pixel jitter. The surface roughness of 16 images of the workpiece profile was determined to investigate the effect of these errors.

The average values of R_a and R_q in presence of different ambient vibration were found to be 1.84 and 2.24 µm, respectively, and the deviation between the 16 values of R_a and R_q determined using the vision method is 2% and 0.8%, respectively. This deviation is expected to be small because vibration or random movement will only cause slight blurring of the image capture at a rate of 25 frames/s (0.04 s/frame). The profile of the workpiece surface can be recovered by applying filtering and thresholding. Since the deviations in R_a and R_q are small, the system can be considered not to be seriously affected by environmental disturbances.

Fig. 10 Actual and measured profiles using stylus method



5 General remarks on comparison between stylus method and machine vision method of roughness measurement of turned parts

The very nature of the stylus method in which a tip of finite radius (usually 2 μm nominal) is drawn across the surface being measured renders the technique inaccurate. The reason is because the tip is not able to penetrate deep into the grooves due to its nose radius as shown in Fig. 10. This results in only approximate measurement of the actual surface roughness. Unlike the stylus method, the proposed vision based measurement determines roughness values using each pixel on the trace, thus producing a more accurate result. A difference in the results obtained using the two measurement methods can be expected even before the measurement is carried out. This is because the stylus method does not extract roughness data from every point on the trace but relies on the stylus tip radius. Also, while the data used in computing the roughness value in a stylus instrument depends on the data sampling rate, a 2-D profile extracted from an image provides data at every pixel. Thus, the measurement accuracy can be improved further using a higher resolution camera. However, the roughness measurement method proposed in this work is applicable only for turned (cylindrical) parts.

6 Conclusion

The stylus type roughness tester is widely used for measuring the roughness of turned parts. Since turned parts are axisymmetrical, a single trace along the workpiece is sufficient. Vision-based roughness measurement has several advantages over the conventional stylus method. Existing methods of vision-based measurement derives data either from an area on the turned workpiece or a line scan of gray value intensity. By simply using a 2-D image of the side of the workpiece, a profile can be extracted that gives accurate roughness information. This method can be extended to developing a stand-alone vision-based roughness tester used to measure roughness offline or implemented to measure roughness on the machine. With the dropping cost of cameras and frame grabbers, vision-based methods of measurement have significant potential for industrial application. However, a new standard needs to be developed before such a technique becomes widely acceptable in the industries.

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