

Figure 1. Photometric stereo system

When three images with the same view are taken under different lighting directions, three reflectance maps are provided for solving a linear system of three unknown surface normals (n_x, n_y, n_z) . The cosine of the incident angle can also be denoted as dot product, as shown in Eq. (2), where \vec{S} represents the unit vector of light source direction and the unit vector \vec{N} represents the surface normal:

$$I = \rho(\vec{S} \cdot \vec{N}) \quad (2)$$

In case of three images being utilized by the measurement system,

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \rho \begin{bmatrix} s_{x1} & s_{y1} & s_{z1} \\ s_{x2} & s_{y2} & s_{z2} \\ s_{x3} & s_{y3} & s_{z3} \end{bmatrix} \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} \quad (3)$$

In Eq. (3), (I_1, I_2, I_3) represent the image intensity values at image location (x, y) . Unknown surface albedo is denoted by ρ . The unknown components of the surface normal is represented by (n_x, n_y, n_z) , and (s_x, s_y, s_z) are the known components of light source vector, where numbers 1, 2 and 3 indicate light direction. To solve the unknown surface reflectance factor and surface normal, the following relation has to be used:

$$\vec{I}(x, y) = \rho(x, y)[S]\vec{N}(x, y) \quad (4)$$

To determine the surface normal, N , in Eq. (4), the following relation can be utilized from Eq. (5), where the lighting directions, S , must not be coplanar to a plane.

$$\vec{N}(x, y) = \frac{1}{\rho(x, y)} [S]^{-1} \vec{I}(x, y) \quad (5)$$

The least squares technique can be utilized to calculate Pseudo-Inverse and local surface gradients $p(x, y)$ and $q(x, y)$. The local surface normal $\vec{N}(x, y)$ can also be calculated from the Pseudo-Inverse using Eqs. (6)-(8) where $\vec{M}(x, y) = (m_1(x, y), m_2(x, y), m_3(x, y))$.

$$\vec{M}(x, y) = \rho(x, y)\vec{N}(x, y) = ([S]^T[S])^{-1}[S]^T\vec{I}(x, y) \quad (6)$$

$$p(x, y) = \frac{m_1(x, y)}{m_3(x, y)}, \quad q(x, y) = \frac{m_2(x, y)}{m_3(x, y)} \quad (7)$$

$$N(x, y) = \frac{p(x, y), q(x, y), 1}{\sqrt{p(x, y)^2 + q(x, y)^2 + 1}} \quad (8)$$

Surface Texture

Surface measurement usually yields the information in two types, i.e. the roughness and the waviness. These parameters can be used to explain and predict the performance and problems of machine tools. Filtering techniques are applied to separate roughness and waviness from the surface topography.

The surface profile parameters are defined by ISO 4287:1997 which encompasses five groups of texture parameters, including amplitude parameters (peak and valley), amplitude parameter (average of ordinates), spacing parameters, hybrid parameters, and curves and related parameters [11].

The surface roughness parameter used throughout this study is the arithmetical mean of the surface profile (R_a). This parameter is also the most widely used surface finish parameter by researchers and industries. R_a is the arithmetic average of the absolute value of the heights of roughness irregularities from the mean value measured [8] [9, p.7]. It can be described in mathematical function as

$$R_a = \frac{1}{N} \sum_{i=1}^N |Z_i| \quad (9)$$

where Z_i is the height of roughness irregularities from the mean value and N is the number of measured points in a sampling length. R_a value can be calculated from the mean height [9].

3. System Designs

Optimal Lighting Position

Spence and Chantler [6] worked with three lights of equal slant and using numerical optimisation they concluded that the normals are best recreated when the light sources are 120° apart, and of slant 55°. This corresponds to orthogonal light directions and is in full agreement with the results derived from the theory presented here.

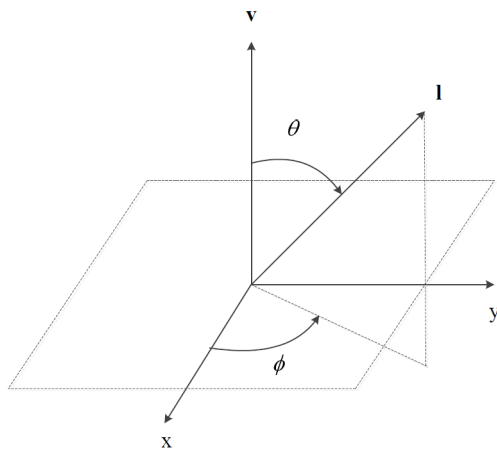


Figure 2. Slant and tilt of a light source

In figure 2, the angle between light source (**I**) and viewing vector (**v**) is the slant angle (θ). Tilt (ϕ) is the angle between the projection of **I** onto the viewing plane (x - y) and the x -axis.

Proposed Photometric Stereo System

Fig. 3 illustrates the PS system set up on the Coordinate measuring machine (CMM) for surface roughness measurement. The roughness standard is mounted at centre of the measuring table. The light source is assumed to be a point source with a constant incident illumination over the scene.

The purpose of the experimental work was to investigate the practical application of PS techniques for measuring R_a from surface texture. The nominal values of standard surface roughness which included 12.5 μm , 25 and 50 μm were applied to validate the PS system. Three differing standard surface roughness was viewed by a vision system constrained pose as their position. The light source was attached with the CMM's probe, which was able to move tilt and slant angles. The sensitivity of the technique to the slant angle was investigated. Three slant angles were examined: $\theta = 37.5^\circ, 45^\circ$ and 52.5° . The optimal illumination configuration with regard to tilt angle is considered to be an intuitive result since the three vectors are equally spaced at 120° apart.

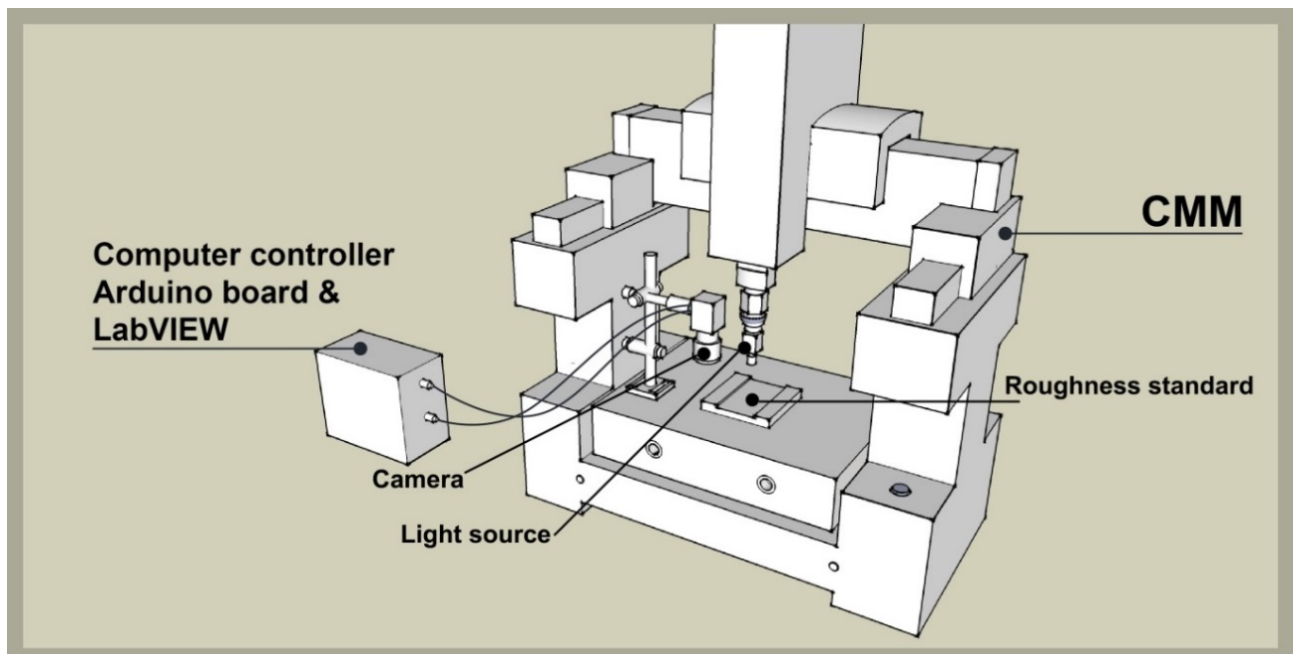


Figure 3. The PS system on the CMM for measuring surface texture

Measurement Method

Using the PS method for measuring surface texture can be written as block diagrams in Fig. 4.

The block diagrams show the six steps for measurement method. The Kingbright 52 mm cluster is used as the light source to create a stable and well-controlled illumination condition. The images with a dimensional size 512×320 pixel are captured from the Basler Ace Digital Gigabit Ethernet camera with a $16\times$ optical zoom lens. Those images acquired from each tilt angle are precisely performed by the CMM's movement. In case of mark images, the area of interest is selected by Matlab programming. Gradient space plots are generated and analysed for all standard surface roughness. The surface normal is therefore calculated by the least squares technique following by Eq. (8). Therefore, accurate shape reconstruction results can be achieved. Twelve lines on the scene coming from pixel points are then chosen for intensity calculation and compared with the

roughness standards.

4. Experimental Results

Estimated Average Surface Roughness Profile

In this research, all images were acquired in a darkroom so that the influence of unwanted extra light was prevented in the scenes. The three nominal values of surface roughness standard Type D following ISO 5436-1 were utilized as the reference of our system.

The original scenes of the surface roughness standard fewer than three light directions are shown in Fig. 6. The idealised simulated surface roughness standard from the PS system is shown in Fig. 7. The 3D recovery of the surface roughness standard measured using from the PS system is illustrated in Fig. 8.



Figure 4. Inspection strategy

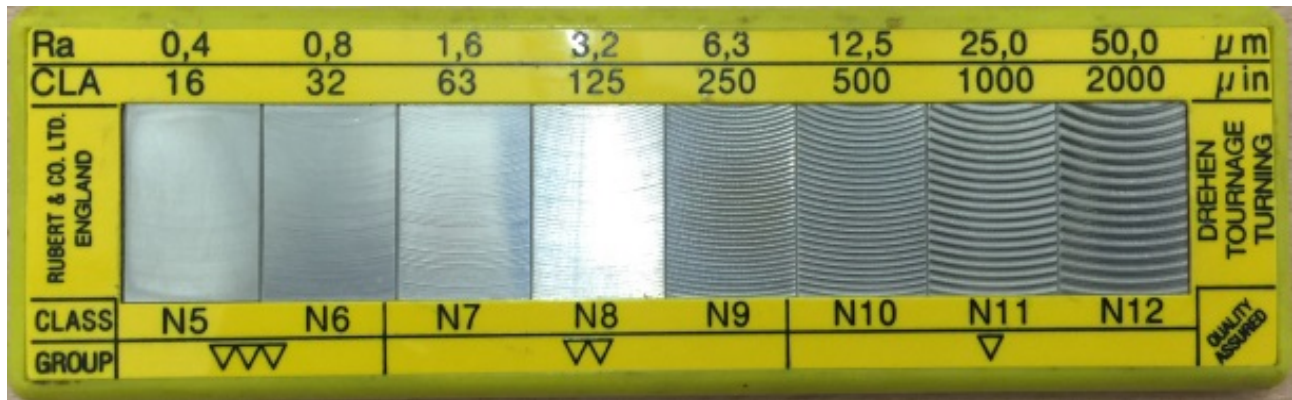


Figure 5. Surface roughness standard Type D following ISO 5436-1

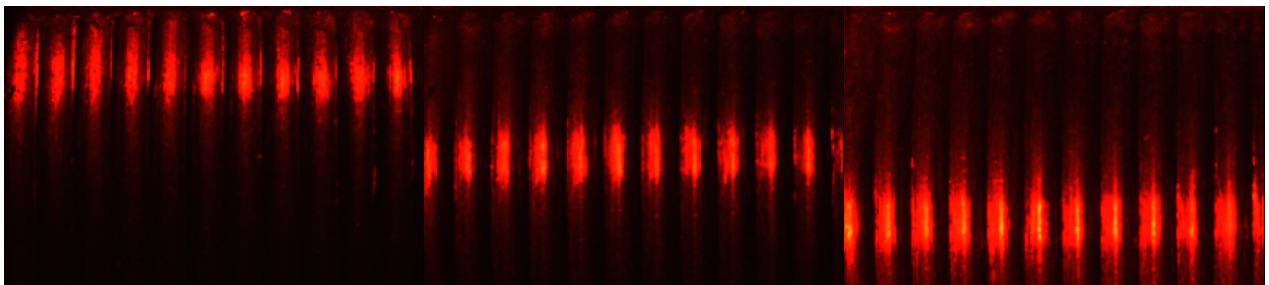


Figure 6. Three images of surface roughness standard illuminated from tilt angle 0° , 120° and 240°

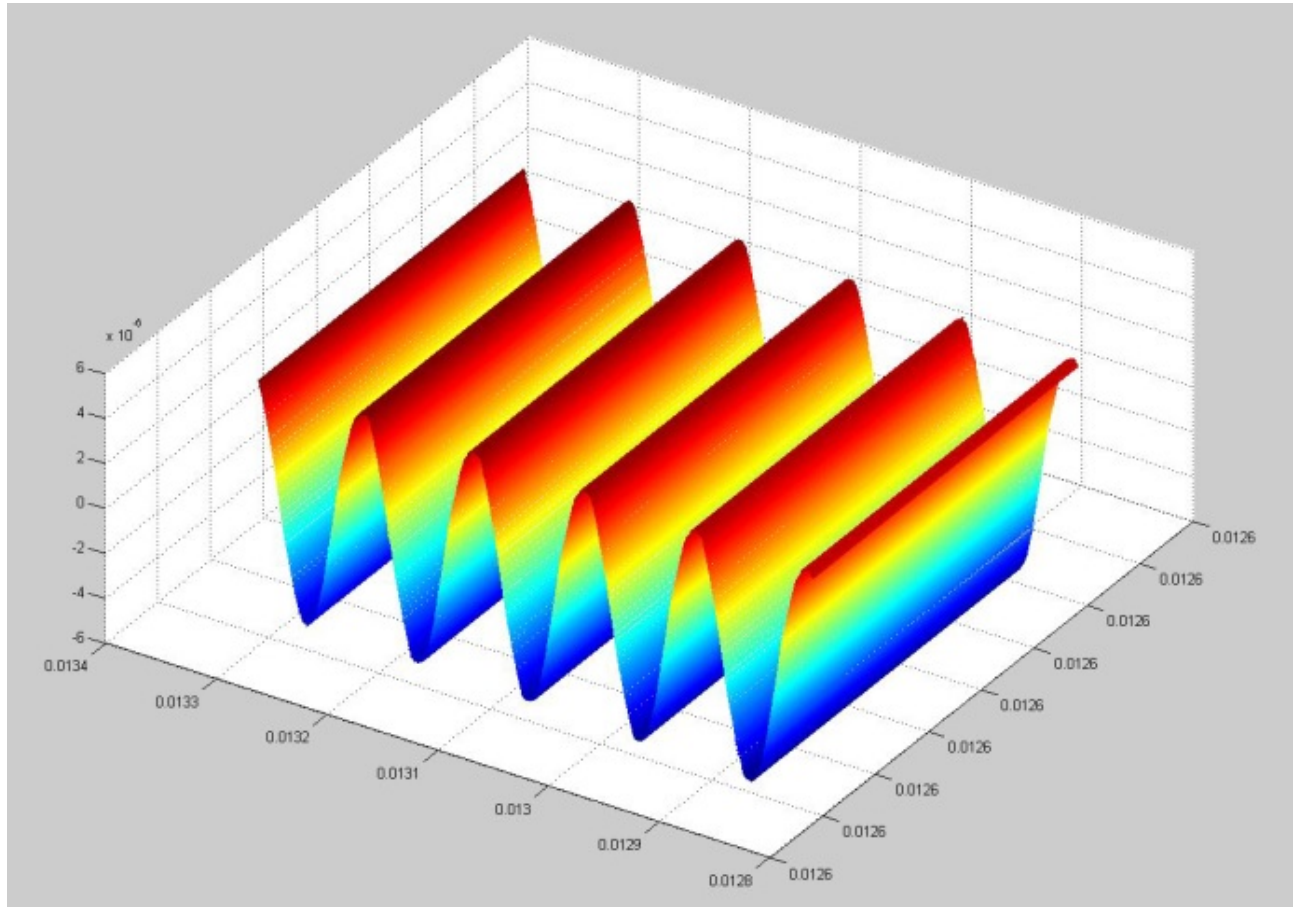


Figure 7. Idealised simulated surface roughness standard

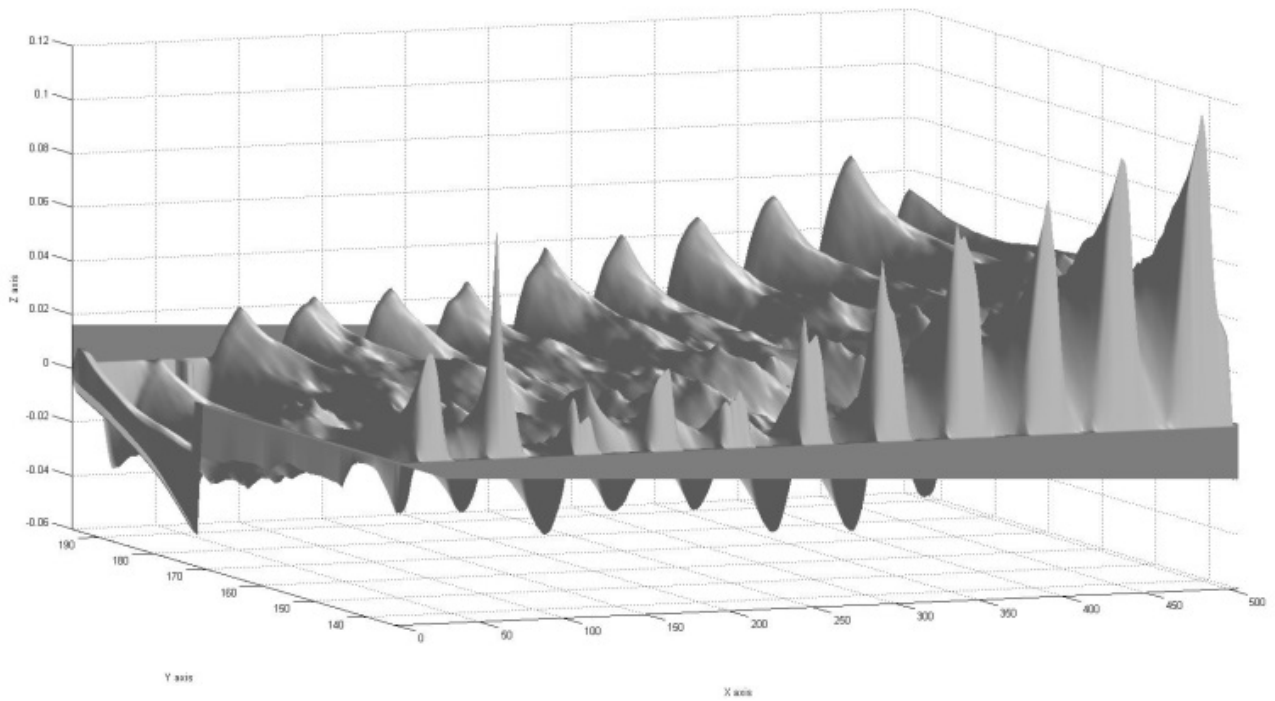


Figure 8. Recovered three dimensional surface roughness standard

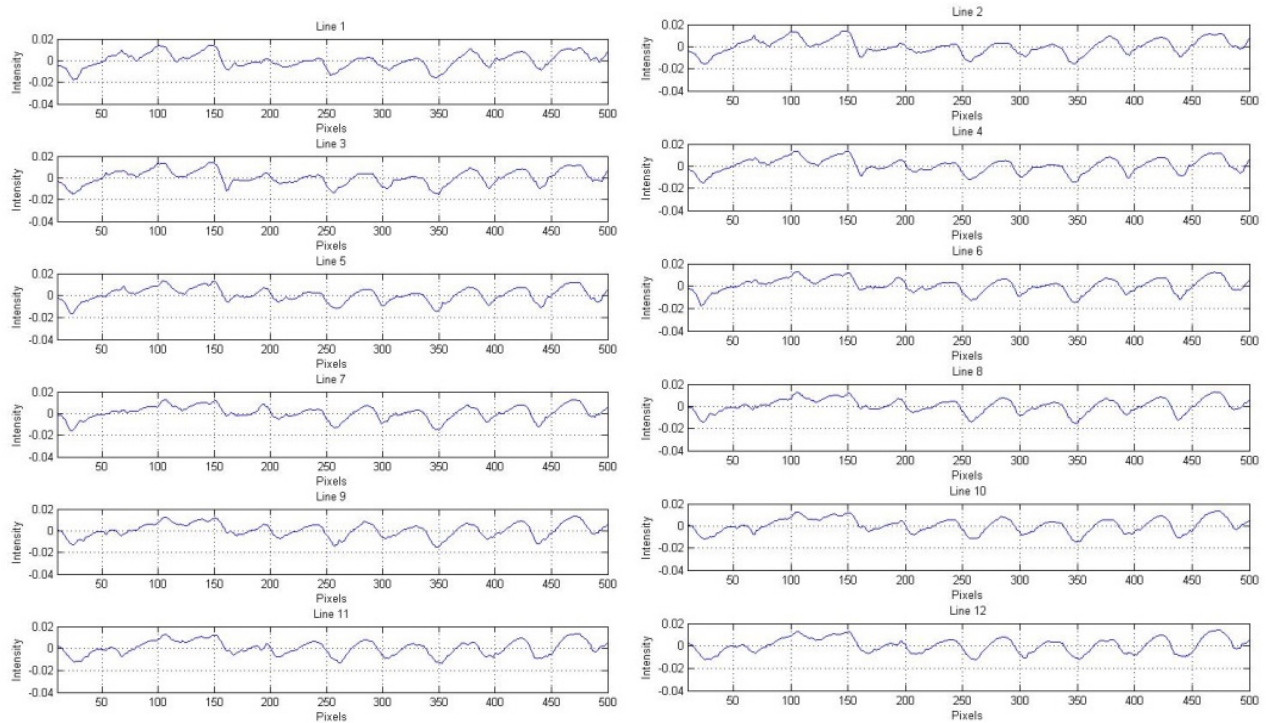


Figure 9. Surface roughness profiles

Computing Average Surface Roughness Using Photometric Stereo Method

The sample profiles are captured, with its centre coincides with the image centre. Each image acquired from the camera covers an area of specimen around 512×340 mm. The average value 12 lines from the simple profiles are then calculated according to ISO 4288:1996. For each value of surface texture, the best coefficient of linear regression is verified with the profiles. The results of measurement are summarized in Table 1 as the coefficients of determination between the estimated R_a by the PS system against the nominal value from surface roughness standard.

Table 1. Linear Regression between nominal value of surface roughness standard and PS technique results under different slant angles

Slant angle (θ)	Linear regression model	Coefficient of determination
37.5°	$R_{a_{std}} = -3040.5R_{a_{PS}} + 438.42$	0.94
45°	$R_{a_{std}} = -1632.4R_{a_{PS}} + 243.23$	0.97
52.5°	$R_{a_{std}} = -1116.3R_{a_{PS}} + 114.71$	0.99

Where $R_{a_{PS}}$ is roughness standard profiles which are averaged from 12 lines from image measurement system, and $R_{a_{std}}$ is nominal values which are identified surface roughness standard. Three values of surface roughness standards were utilized for evaluation of the PS system. The best coefficient was found at 52.5° of slant angle. This equation was offered for roughness average estimation from recovered surface. Furthermore, more information on surface characteristics would be presented from three-dimensional (3D) surface textural patterns of the surface roughness standard.

5. Conclusions

The experiment results have shown that the new approach for textural examination using photometric stereo can measure surface roughness of work pieces. However, the results from comparison experiments would be able to increase accuracy by surface roughness standard calibration. In fact, more experimental cases have to be considered and compared with the present method of analysis. In addition, the measurement uncertainty using the PS system should be calculated.

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