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A Robust Algorithm for Roughness Laser Measurement based on Light Power Regulation against Specimen Changes

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Methods for measuring surface roughness based on light reflectivity have advantages over methods based on light interference or diffraction, especially in in-situ, on-the-machine and in-process applications. However, measurement inconsistencies caused by changes in the specimen are still a drawback for field applications. In this study, we propose a new feedback-based algorithm to enhance the consistency against changes in the specimen. The algorithm is deduced from simulations based on light reflectance theory with typical modeled surfaces. The proposed method is similar to a digital controller and regulates the power of reflected light. Experiments varying heights and materials, verified the improvements in robustness of the method against measurement disturbances caused by specimen changes.

Key Words : Surface Roughness, Reflected Laser Beam, Measurement Robustness, Power Regulating, Feedback Control, Specimen Changes

Nomenclature

$R_{q,smooth}$	Roughness for mirror-like surfaces
$R_{q,rough}$	Roughness for relatively rough surfaces compared to mirror-like surfaces
R_q	Blended surface roughness (Root-mean-square) of $R_{q,smooth}$ and $R_{q,rough}$
L_r	Light intensity of reflected light
E_1	A magnitude of incident electric field (A measure of a laser power)
σ	Standard deviation of a light intensity distribution of reflected light
θ_i	Incident angle of light on a surface
θ_r	Reflection angle of light on a surface
λ	Wavelength of incident light
T	Correlation distance of surface model
σ_h	Standard deviation of surface model
P_r	Normalization of totally reflected light's intensities

1. Introduction

Surface roughness is an important parameter in product design and directly affects the quality of the manufactured product (Park and Ahn, 1997), thus a fast and reliable technique to measure roughness is needed for enhanced productivity and maintenance. Many researches confirm the laser surface-roughness measurement method based on light reflectivity as efficient, especially in field applications, as compared to light interference- or diffraction- based methods (TAKAHASHI et al., 2002 ; HARADA et al., 2002). Although the reflectivity-based method is known to be more robust than other optical measurement

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techniques against environmental disturbances, it is still not sufficiently accurate enough to be used in manufacturing.

Causes that can lower the robustness of a measurement can be classified into two groups. The first group encompasses how well the fabrication of the optical probe suits the parameterization of surface roughness. An example of the parameterization rule can be found in (Yim and Kim, 1988). The second group encompasses problems that result from changes in the state of the specimen. These include changes to the material (or reflectivity), surface orientation (or tilting and bending), specimen's dimensions (or surface height from light source), and surface cleanness. Although the accuracy of the measurement can be disturbed by all of them, the specimen's height and material can be most disruptive since the others can be restricted to the optimal states or conditions at initial set-up or fabrication. The specimen's height varies during the removal process, eg. grinding, and also the specimen's material can vary according to manufacturing specifications. Because surface measurement techniques based on the principle of light reflectivity are mostly used in in-process and on-the-machine applications, the usual but inevitable variations in the specimen's height and material can be considered as principal sources of degraded reliability. Shen (2001) tried to solve the specimen's material problems by applying different correlation rules to each material, but unique parameterization rules cannot be formulated for all surfaces and cannot accommodate in-situ measurement needs.

The unexpected changes to the specimen's height and material lead to un-anticipate changes in the reflected light, and consequently the parameterization rule misinterprets correlations between reflected light and surface roughness. Another significant problem in the situation is sensor capacity. An image sensor is normally used to acquire the distribution of the intensity of the reflected light. However, each pixel on an image sensor has very short linear measuring range, thus when the sensor is exposed to light that is outside of its range, the information it reports is frequently distorted and as a consequence critically harms the measurement consistency.

In this study, after observing how changes in the specimens affected light reflection, a new algorithm to enhance the measurement robustness and accuracy was proposed. The algorithm, which is based on an incident light power adjustment, is similar to a power regulator because it maintains the reflected light power within certain levels, in which region light intensities are correctly measured by an image sensor. We simulated the mutual relationship between variations in incident and reflected lights versus modeled surfaces, and then embedded the proposed algorithm into an optical probe. Experiments were conducted on specimens of different materials with differing heights in order to verify the enhancements of measurement consistency.

2. Light Reflectance and Roughness Parameterization for Modeled Specimens

2.1 Models for light reflectance and image sensor

When light reflects from a surface, the reflection angles are subordinate to the surface's geometric variations, thus many researchers have proposed suitable surface models in order to correctly formulate light reflectance. Beckmann and Spizzichino (1963) established a light reflectance model on the basis of modeling surfaces with electromagnetic wave theory. This model has a mean height value, $\langle h \rangle = 0$, standard height deviation (or surface roughness), σ_h, and a distance between height peaks (or correlation distance), T. Nayer (1991) revised Beckmann's model as shown in Eq. (1) by appending an additional imaging optical system in order to apply it to machine vision. The assumed imaging system has some parameters; z is the distance between the surface and focusing lens, f is the distance between lens and image sensor, and dA_{im} is the pixel area of image sensor, and γ is a solid angle at the center of the lens.

$$L_r=\sqrt{\frac{\mu}{\varepsilon}}\frac{E_1^2\cos^2\theta_i}{2\lambda^2}e^{-g}\left(\left(\frac{z}{f}\right)^2\frac{dA_{im}\cos\gamma}{\cos^2\theta_r}\rho_o^2 + \frac{\pi T^2D^2}{\cos\theta_r}\sum_{m=1}^{m=\infty}\frac{g^m}{m!m}e^{-v_{xy}^2T^2/4m}\right) \tag{1}$$

However, Nayer's model ignored the linearity of the image sensor, thus we added region constraints $L_{r,\min}$, $L_{r,\max}$ for a linearly sensible light intensity (L_r) between incident light power (E_1) E_L and E_U as shown in Eq. (2).

$$L_r=\begin{cases} L_{r,\max} & (E_1>E_U) \\ CE_1 & (E_L\le E_1\le E_U),\ C\text{: Constant} \\ L_{r,\min} & (E_1<E_L) \end{cases} \tag{2}$$

2.2 Roughness correlations based on light decomposition

Shen (1999) recognized a correlation between the surface roughness and the diffuseness of a reflected light's pattern, and he associated standard deviation, σ, of the intensity distribution with surface roughness $R_{q,rough}$. However, these parameters assume that surfaces are relatively rough, thus we advanced the parameterization by decomposing specular light magnitude with incident light power, E_1, and measured the mirror-like surface's roughness, $R_{q,smooth}$ (Seo et al., 2004). Equation (3) gives the correlations for smooth and rough surfaces by parameter (a_1, b_1), (a_2, b_2), respectively.

$$\begin{cases} R_{q,smooth}=a_1E_1+b_1 \\ R_{q,rough}=a_2\sigma+b_2 \end{cases} \tag{3}$$

Heterogeneous representation of each surface in Eq. (3) cannot harmonize their measurements in the intermediate surface region where specular and diffuse light components coexist, thus the roughness formulations were seamlessly joined into blended roughness, R_q, as expressed in Eq. (4) and Eq. (5) where coefficients w_1 and w_2 are defined. (Seo and Ahn, 2004)

$$R_q=w_1R_{q,smooth}+w_2R_{q,rough} \tag{4}$$

$$\begin{cases} w_1=1-\left(\frac{1}{2}(\tanh((-r+r_c)/t)+1)\right)^n \\ w_2=1-\left(\frac{1}{2}(\tanh(r-r_c)/t)+1)\right)^m \end{cases} \tag{5}$$

2.3 Simulations of reflected light variations versus incident light power changes

Changes in a specimen's height or material (Light reflectivity) have something in common with incident light power changes. Even though those specimen's changes do not alternate the incident light power in itself, sensors register an alteration. Therefore, a simulation based on incident light power variations can provide a good inference about the mutual relationship between specimen's changes and light reflectance.

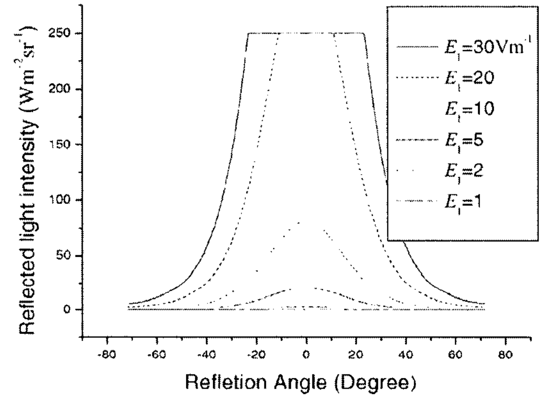


Fig. 1 Simulation results of light intensity formations on a principal-axis

Figure 1 shows reflected light intensity distributions formed on a principal-axis, which describes principally reflected light direction as a coordinate of the imaging plane. These simulation results reveal that all of the light intensity could be clearly formed within a very short sensible

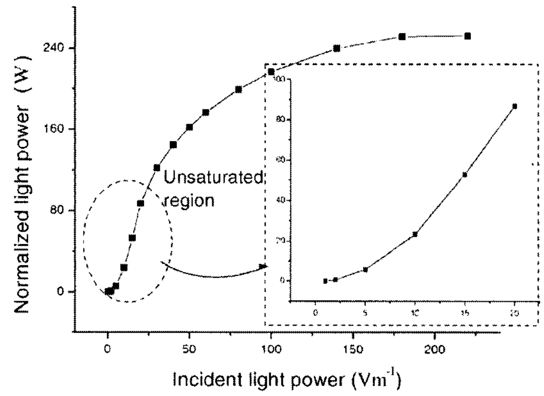


Fig. 2 Simulation results for normalized reflected light power (P_r) variations

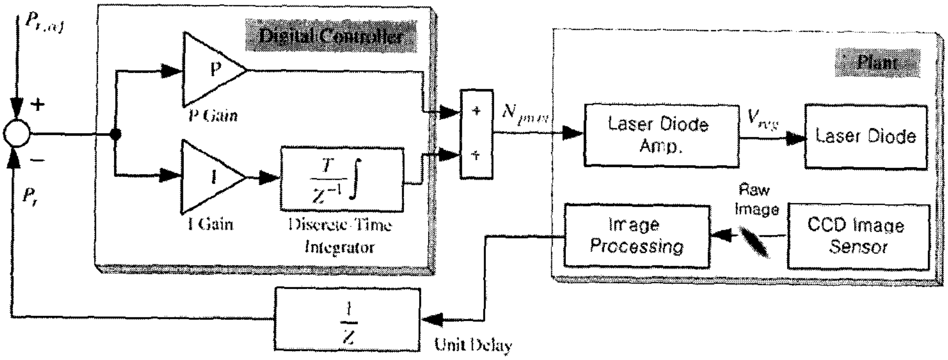


Fig. 3 Block diagram for proposed regulating algorithm

region only. To determine which region, the reflected light changes were parameterized as power variations, P_r, which have been formulated to denote a normalization of the intensity of the total reflected light. Figure 2 shows the variations of P_r versus incident light power changes, and gives the narrow sensible region. These simulation results indicate that some adjustments are needed in order to form light intensities correctly within the sensible region under the influence of sensor saturation or ambient light.

3. Algorithm for Regulating Reflected Light Power

In the previous simulations important disturbances to the robustness of the roughness measurements should be noted. In order to force light intensities to remain within the sensor's sensible region, P_r was regulated by properly controlling its incident light power. Because the parameter P_r is deeply related to the sensible region versus incident light power as shown in the simulation results, this approach should be suitable.

Figure 3 shows a block diagram of proposed algorithms designed to regulate P_r. The feedback-based algorithm is basically a digital controller based on PID control theorem. Gains in controller can be selected by using the Ziegler-Nichols tuning method (Dorf and Bishop, 1995), and its detail derivation can be found in (Seo et al., 2004). Figure 4 shows the performance test results for a given reference input $P_{r,ref}$ using a mirror as a real specimen. The figure shows a smooth settlement with a slight steady-state error that is smaller than the optical probe error.

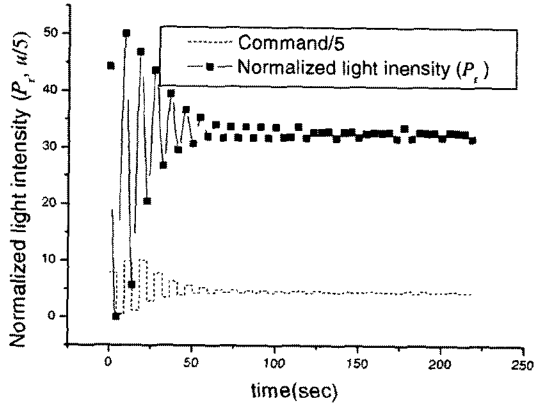


Fig. 4 Control performance of proposed regulator

4. Experimental System's Set-up and Method

Figure 5 shows the schematic diagram of an experimental system. The equipment consisting of a laser diode, a beam splitter, and a CMOS image sensor is driven by a micro-controller, and furthermore can be linked to a personal computer. Figure 6 shows a laser diode driver that controls an incident light power as it plays important roles in implementing the algorithm. Tables 1 and 2 summarize the specifications of the image sensor and the laser diode, respectively.

The proposed algorithm has been tested with respect to the specimen's height and material changes for its ability to regulate performance and enhance robustness. In order to simulate changes to

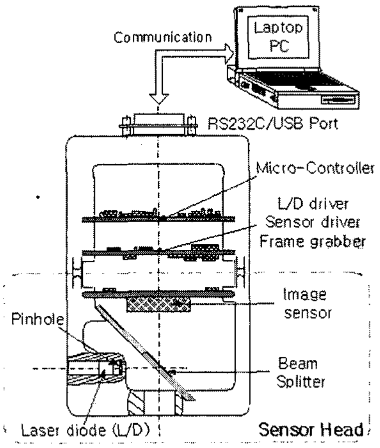


Fig. 5 Schematic diagram of experimental system implemented for image formation

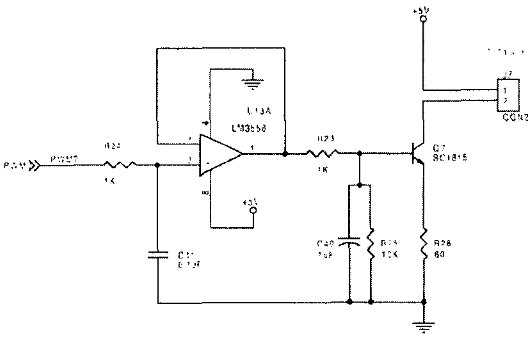


Fig. 6 Laser diode driver circuit for PWM control

Table 1 Specifications of HV7131D CMOS image sensor

Pixel resolution	642×482
Pixel size	8×8 μm^2
Fill factor	30%
Format	VGA
Sensitivity	2.5V/lux·sec
Technology	0.5 μm 2 metal CMOS

Table 2 Specifications of LT052 Laser diode

Optical power output	35 mW max.
Wavelength	650 nm band
Operating current	110 mA max.

Table 3 Experimental conditions for height changes

Initial light power	21 mW (60% of full power)	
Height changes	3~28 mm	
Sampling interval	4.5 sec	
Standard specimens (Plastic material)	#1	R_q 0.08 μm
	#2	R_q 0.19 μm

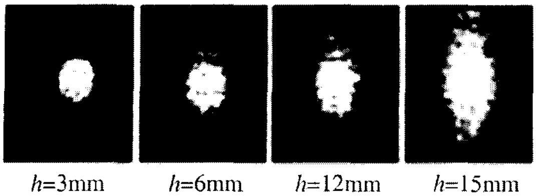
the specimen's height, the optical probe's height was changed. The experimental conditions for height changes are shown in Table 3. Specimen's made of three materials, SKD11, Super-alloy, and Silicon-wafer, were used and were polished to a variety of surface roughnesses. A stylus-type measurement device, SJ-301 made by Mitutoyo Co. Ltd., was used to provide the reference roughness, $R_{q,ref}$. In the experiments, roughness measurements were performed 5~6 times at different points on each specimen, and then averaged to remove irregularities caused by the laser surface spot, which was projected through a pinhole as small as 0.8 mm. The roughness correlation parameters in Eq. (3), (a_1, b_1) and (a_2, b_2), were fixed at (0.0632, −2.4557) and (0.0068, −0.0055), respectively, and the blending coefficients in Eq. (5), (t, r_c), (n, m), were fixed at (−0.012, 0.145), (1.5, 1.5), respectively.

5. Experimental Results

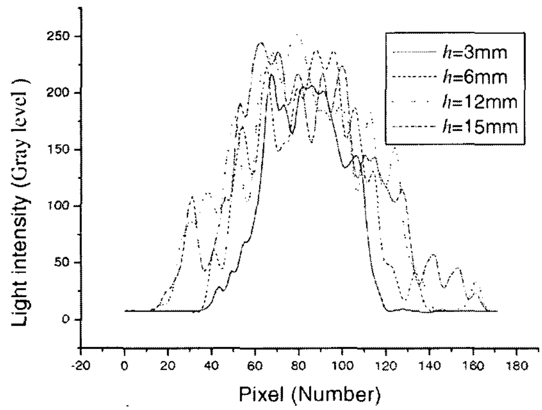
5.1 Immunity to height disturbance

Figure 7(a) shows images of reflected light intensities. The sensed patterns are enlarged according changes in height, as an incident light power is enhanced to compensate for the weakened reflected light intensities. As shown in Fig. 7(b), the light intensity distributions on a principal axis are correctly formed without sensor saturation or ambiguity.

Figure 8 shows the variations of the measured surface roughnesses of specimens #1 and #2 versus height changes and it clearly proves the robustness of the proposed measurement algorithm. The results are consistent below about 15 mm. At greater heights, the reflected image is too large to capture by the sensor and measurements become unstable, thus it can be said that the results are valid when the captured image pattern is in its integrity.



(a) Images of reflected light



(b) Light intensity distributions on a principal-axis

Fig. 7 Reflected light images and their intensity distributions versus different heights (*h*)

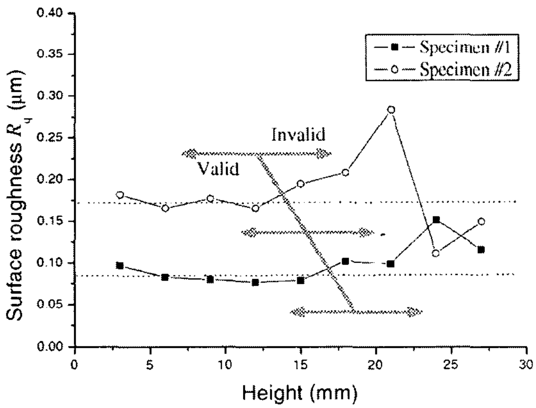


Fig. 8 Measured surface roughnesses for standard specimens and their immunities to height variations

5.2 Immunity to material disturbance

Tables 4, 5, and 6 summarize the measurement results of the specular and diffuse components, E_1, σ and their roughness correlations, $R_{q,smooth}$, $R_{q,rough}$ for the polished specimens of different materials. In spite of applying the unique roughness parameterization rule to various materials, the measurement errors for blended roughness, R_q with the reference roughness, $R_{q,ref}$ are as small as ±10 nm. Therefore, the proposed algo-

Table 4 Experimental results from SKD11 (μm)

$R_{q,ref}$	E_1	σ	$R_{q,smooth}$	$R_{q,rough}$	R_q
0.02	39.14	12.50	0.02	0.08	0.02
0.03	39.31	11.37	0.03	0.07	0.03
0.04	39.41	11.38	0.04	0.07	0.04
0.07	39.85	12.88	0.06	0.08	0.06
0.08	40.09	14.56	0.08	0.09	0.08
0.09	40.27	15.01	0.09	0.10	0.09
0.11	40.50	16.43	0.10	0.11	0.10
0.15	40.59	18.04	0.11	0.12	0.15
0.18	40.77	28.76	0.12	0.19	0.19
0.23	40.89	38.32	0.13	0.26	0.26
0.31	40.96	47.66	0.13	0.32	0.32

Table 5 Experimental results from Super-alloy (μm)

$R_{q,ref}$	E_1	σ	$R_{q,smooth}$	$R_{q,rough}$	R_q
0.04	39.55	11.38	0.04	0.07	0.04
0.07	39.81	12.88	0.06	0.08	0.06
0.10	40.32	18.44	0.10	0.12	0.10
0.15	40.60	20.03	0.11	0.13	0.15
0.18	40.79	26.53	0.12	0.17	0.17
0.28	40.93	43.30	0.13	0.29	0.29

Table 6 Experimental results from silicon-wafer (μm)

$R_{q,ref}$	E_1	σ	$R_{q,smooth}$	$R_{q,rough}$	R_q
0.02	39.18	7.91	0.02	0.05	0.02
0.04	39.52	9.26	0.04	0.06	0.04
0.06	39.93	11.19	0.07	0.07	0.07
0.08	40.15	11.43	0.08	0.07	0.08
0.09	40.30	13.85	0.09	0.09	0.09
0.10	40.36	14.46	0.09	0.09	0.09
0.11	40.50	15.53	0.10	0.10	0.10
0.15	40.76	17.19	0.12	0.11	0.14
0.18	40.82	26.38	0.12	0.17	0.17
0.20	40.91	29.54	0.13	0.19	0.19
0.25	41.12	36.71	0.14	0.24	0.24
0.30	41.24	47.46	0.15	0.31	0.31

rithm maintains measurement consistency for changes in surface reflectivity.

6. Conclusions

The mutual relationship between variations in incident and reflected light as based on light reflectance theory were discovered by modeled specimens. The results of the simulations were used to formulate a feed-back algorithm to compensate for disturbances caused by changes to a specimen's height and material. Experiments verified that the proposed algorithm could successfully enhance the consistency of the measurement's accuracy and also improve its adaptability to field-applications without resetting the roughness parameterization rule. Conclusions from the simulations and experiments are as follows :

(1) Regulating reflected light power within certain levels can reform the distorted light intensity distribution and provide a basis for algorithm formation.

(2) In order to formulate an algorithm, controlling incident light based on power feedback is efficient for regulating light reflection.

(3) The proposed algorithm maintains measurement consistency and accuracy for changes to the specimen's height up to 15 mm and changes in materials such as SKD11, Super-alloy and Silicon-wafer.

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