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Portable non-contact surface roughness measuring device

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Abstract. This paper outlines a development of non-contact surface roughness measuring tool by using non-contact method. Major works involve development of the non-contact surface roughness measuring tool toward flat surface. Non-contact method was developed to prevent damage and scratch from the workpiece. In order to develop the tool, optical sensor is used as the input signal for microcontroller. Voltage signal received from optical signal is translated into surface roughness measurement value by using mathematical formula. C++ language programming is used as the code instruction for Arduino microcontroller. The results indicate that the developed tool is capable to measure surface roughness for flat surface metal with non-contact method.

1. Introduction

These Ra and RMS are both unit representations for surface roughness. Ra is a component of surface texture which is used to quantify by the vertical deviation of the surface compared to the real surface in its ideal form. It is one of the important key parameters for quality control in manufacturing processes. A surface mainly consist series of peaks created by the lay through machining and finishing processes. Machined surface produced several combinations of surface texture components which include lay, waviness, and roughness [1] as illustrated in Figure 1.

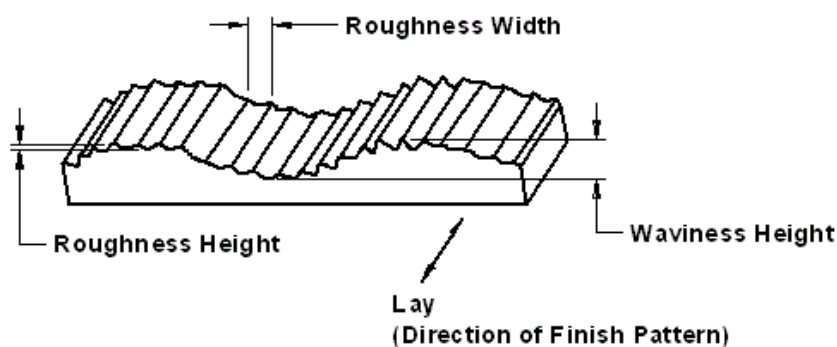


Figure 1. Surface texture made of different components [2].

Lay represent the direction of predominant surface pattern which can be used to determine the machining operation performed on the surface. Waviness is widely spaced component which is the result from noise produce during the machining process such as vibration, tool deflection and thermal

distortion [2]. Roughness is a result of impression of the cutting tools to the surface which cause irregularities. There are various types of surface roughness measuring equipment categorized as non-contact method available in the market. These machines are usually in a bench top or workstation configuration which considered big and bulky. The instrument is not able to measure surface roughness directly on the surface of interest of a large object. The current configuration also causes the limitation in the size of the specimen that can be measured. Sample which is bigger than the stage of the instrument is impossible to be measured unless a small section of the sample is cut out. However, cutting small sample in most of the time is not permitted as it will cause permanent damage to the original sample [3]. Therefore, this development intended to introduce a portable surface roughness measurement tool with application of Arduino microcontroller.

Conventional way to measure surface roughness is by using contact technique which is mechanical stylus surface roughness measuring tool. The stylus is made up of sharp diamond tip with radius as small as 0.001 mm [4]. It touches the surface and traced along a length of perpendicular to the lay. The mechanical stylus produces a consistent measurement and easy to use. However, the sharp stylus tip can eventually scratch the surface which causes permanent damage to the specimen. These disadvantages can be resolved by using non-contact method. There are several mechanisms can be adopted in developing non-contact surface measuring tool. Advancement of controller technologies permitted custom-made development to meet specific purposes of measuring tools.

Total Integrated Scattering (TIS) measures the diffused scattered light intensity to determine the roughness of the surface as shown in Figure 2. A Coblenz sphere is used to collect the diffused scattered light which then directed to the sensor. The range of surface roughness measurement using TIS method depends on the wavelength of the coherent light source used. The system can produce results with high repeatability and accuracy in nanometers scale. The TIS value is calculated by certain formula [14]. By referring to the TIS value, assuming the surface has a Gaussian distribution, the formula can be written as, R_q is the RMS of surface roughness, λ is the light wavelength and θ is the incident beam angle. Experiment by Mazule et al (2011) demonstrated that the method is able to measure a range of surface roughness between 0.1 nm to 10 nm in a vacuum chamber using laser of 0.4 mm diameter [15]. The drawback of this method is that the system is sensitive to particle and dust which required a vacuum chamber to control the air quality and high in maintenance cost.

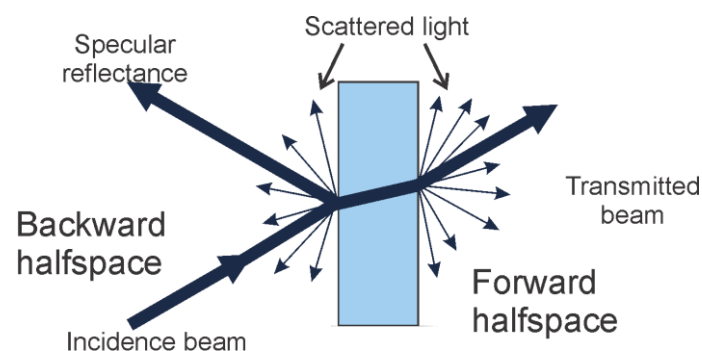


Figure 2: System of TIS method. [14]

Interference method determines the surface roughness by processing the fringe pattern produce by two light waves of different phase. The reflected light from the specimen and reference mirror is recombined to produce an interference fringe pattern. By observing the fringe pattern, the change in phase can be calculated and offset of the rough surface can be determined. Michelson Interferometer uses this principle to measure the height offset of the rough surface as illustrated in Figure 3.

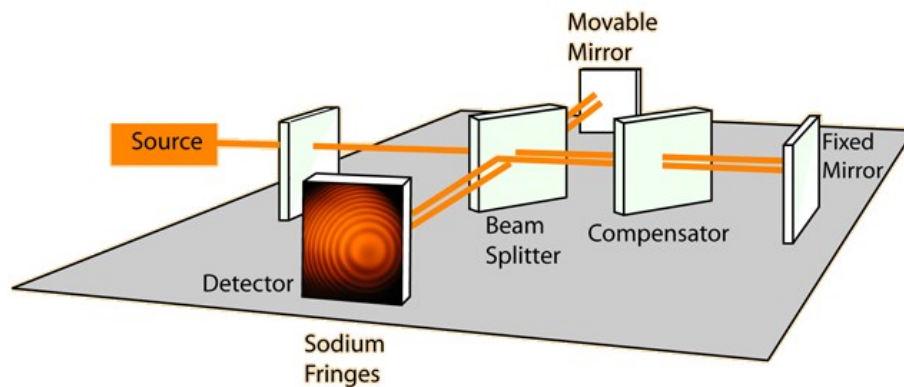


Figure 3: Michelson interferometer [1]

Michelson interferometer splits the light source by using the beam splitter. Some of the beam is directed to the reference fixed path where the reference mirror surface is placed and some of it to the sample surface, S. The reference mirror, R serves the purpose to reflect the beam which is used as reference of the original beam. The beam that is directed to the surface with the distance of $L+\delta$ where δ represent the path length difference is reflected. Then, this beam is combined with the beam from the reference mirror surface and goes into the interferogram [1]. Interference method is sensitive to vibration which will introduce noise to the interference pattern affecting the accuracy of the data. The range of smoothest surface roughness measurable depends on the surface roughness of the reference mirror used. The main piece of system, the Coblenz sphere will cause the design to be big and bulky. Interference method requires a microscope and CCD camera which is connected to the computer to process the image to obtain a 3D plot. The need of software to process the image requires constant connection to the computer which will reduce the portability of the device. Requirement to design a special holder to hold the microscope for vibration reduction will not only increase the size of the device but also the set-up time required for each reading.

Specular reflectance concept measures the surface roughness by measuring the amount of specular reflected light. Coherent light source such as a laser is illuminated on a flat surface at an incident angle of α . Upon reaching the surface, the light is reflected. For an uneven surface profile, the reflected ray is scattered around the direction of specular reflection [5] as shown in Figure 4 and Figure 5. The scattered reflection is called the diffused reflection. The diffused reflected lights are due to the lay of the surface which reflected the lights away from the specular direction. Thus, theoretically the rougher the surface, the lower the intensity of specular reflected lights. The surface roughness RMS and light intensity can be related by using the equation where is light intensity at specular axis, is the total reflectance of rough surface and is the incident ray angle [6] [7] [3]. With the condition that the wavelength of the light source is much larger than the surface roughness intended to be measured [6]. Speckle method determines the surface roughness by speckle contrast of the reflected light. Ratio of bright to dark (B/D) spots can be used to determine the surface roughness. Higher surface roughness, R_a will results in lower B/D ratio and in higher contrast intensity of speckle reflection [8].

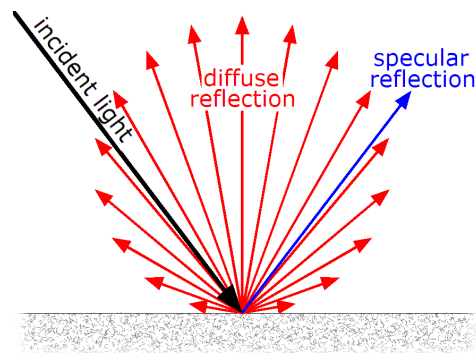


Figure 4: Reflected light in specular and diffused direction [2].

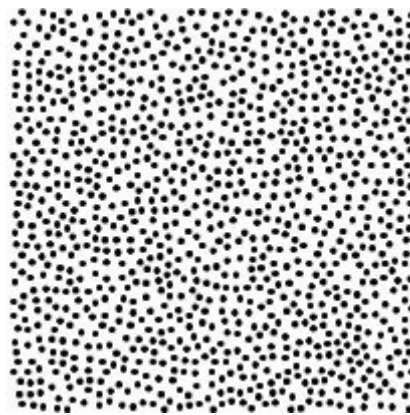


Figure 5: Speckles pattern [9].

This technique has a maximum range of measurable surface roughness which equal to 3 times the wavelength, Λ of the light source [10]. The range of measurement is limited by the optical system [11]. Another research used a linear image sensor to measure the speckle intensity distribution that is reflected by the rough surface and concluded that the speckle intensity has negative correlation with the surface roughness [11]. Further development measured the speckle contrast by image processing [12]. A method named statistical properties of binary images (SPBI) where the speckle image is converted into binary image. The number of bright pixel and dark pixel is calculated and the sum of bright pixel is divided by dark pixel to obtain the bright and dark grayscale intensity ratio, B/D [12]. Specular method in the other hand offers decent range of measurement which depends on the wavelength of the light source used. The system which consists of only a light source and a sensor is simple and suitable to be integrated into a small and compact design. It meets a portability aspect of the device with acceptable performance at a much lower cost compared to the other methods. Little efforts in setting up the device prior the measurement will result in faster measuring time. Thus, this method was adopted to develop the portable non-contact measuring device.

2. Experimental method

In this project, surface roughness measuring tool was developed by using electronic sensors and some other electronic components such as microcontroller and LCD display. Electronic sensors act as input component, while LCD display acts as output component. Both input and output components are connected to microcontroller. Figure 6 shows the block diagram for measuring systems.

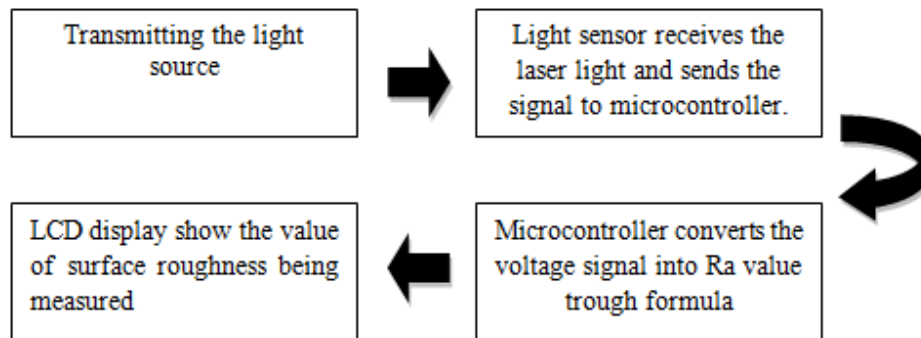


Figure 6. System block diagram.

2.1 Transmitting and receiving process

The red laser diode provides a consistent coherent light source of 650 nm in wavelength which is used to illuminate the specimen. To provide coherent light source, Keyes KY008 laser diode module has been used. This laser diode has an operating voltage of 5V and capable to provide 6mm diameter of red laser with output power of 5mW at wavelength of 650 nm. The coherent light reflected by the surface of the specimen is measured by the digital light sensor. BH1750 light sensor is used to measure the light intensity. This sensor is capable of detecting wavelength of light approximately between 400 nm to 700 nm. The sensor also has a range of 1lux to 65535 lux with resolution of 1 lux with measuring time of average 12 ms.

2.2 Signal converting and output display process

Signal voltage from light sensor is used to calculate the surface roughness value. This voltage signal is sent to microcontroller in lux value of light intensity reading. IDE Arduino software is used to code the Arduino Pro Mini microcontroller and also to communicate with the input component connected. 10 number of lux reading is recorded, summed up and divided by 10 in order to obtain mean specular intensity, \bar{I}_{sp} .

Equation 1 =

$$\frac{\bar{I}_{sp}}{I_o} = \exp\{-(4\pi\sigma \cos \theta / \lambda)^2\} \quad (1)$$

Where,

\bar{I}_{sp} = Mean specular reflectance intensity

I_o = Incidence light intensity

σ = RMS surface roughness

θ = Incidence angle

λ = Wavelength of laser

Equation 1. Surface roughness, Ra formula

The \bar{I}_{sp} value is then substituted to equation 1 to calculate the RMS surface roughness, σ and converted to surface roughness, R_a value. R_a value is calculated by using dividing σ with 1.11. The value of R_a is then displayed to the LCD 16x2 screen as the output.

3. Results and discussion

The table shows the results of surface roughness measured by using the prototype Ramax and Ramin. It is compared to stylus tip 5 μ m stylus profilometer value represented by Rao with different experimentation. The negative sign in the percentage of error range indicate the reading measured by the prototype is lower than the real roughness value measured by mechanical stylus profilometer .

Table 1. 45-degree angle of incident.

Stylus Measured Roughness R_{a_0} (μm)	Measured R_{amin} (μm)	Measured R_{amax} (μm)	Percentage Error Range (%)
0.3423	0.1000	0.1097	-70.78 to -67.95
0.3390	0.0954	0.1061	-71.86 to -68.70
0.1995	0.0932	0.09766	-53.28 to -51.05
0.0891	0	0	0

Table 2. 60-degree angle of incident.

Stylus Measured Roughness R_{a_0} (μm)	Measured R_{amin} (μm)	Measured R_{amax} (μm)	Percentage Error Range (%)
0.3423	0.1572	0.1625	-54.08 to 52.53
0.3390	0.1403	0.1584	-58.61 to -53.27
0.1995	0.1519	0.1577	-23.86 to -20.95
0.0891	0	0	0

With 45° configuration, the percentage of error of the measured reading is as high as 51 % to 71 % as illustrated in the table 1 and Figure 7. While for the 60° configuration as illustrated in table 2, the percentage of error of the measured reading is in between 20.95 % to 58.61 %. From these results, the percentage of error is decreases with the increase in incident angle. The attempt to extend the range of surface roughness measurable as stated up to 0.8 μm and reducing the size of the device by decreasing the incident angle to 45° and 60° is not possible as the errors are very high. Even though it exhibits similar trend where intensity decreases as roughness increases and a more linear correlation [3] the reading is very dispersed which causes a higher error. Thus, range lower than 60 degree is eliminated from the selection. Surface roughness at 0.0891 μm is not measurable as the resolution of the sensor is too low.

Table 3. 78-degree angle of incident.

Stylus Measured Roughness R_{a_0} (μm)	Measured R_{amin} (μm)	Measured R_{amax} (μm)	Percentage Error Range (%)
0.6330	0.5285	0.5372	-16.51 to -15.13
0.4730	0.4715	0.4736	-0.32 to 0.12
0.3423	0.3017	0.3373	-11.86 to -1.46
0.3390	0.3388	0.3482	-0.05 to 2.00
0.1995	0.1969	0.2168	-1.30 to 8.6
0.0891	0	0	0

Table 4. 80-degree angle of incident.

Stylus Measured Roughness R_{a_0} (μm)	Measured R_{amin} (μm)	Measured R_{amax} (μm)	Percentage Error Range (%)
0.6330	0.5388	0.5263	-14.88 to -16.86
0.4730	0.4836	0.4873	2.24 to 3.02
0.3423	0.3553	0.3996	3.80 to 16.73
0.3390	0.2857	0.3277	-15.72 to -3.33
0.1995	0.2728	0.2850	36.74 to 42.85
0.6330	0.5388	0.5263	-14.88 to -16.86

With 78° configuration, the percentage of error of the measured reading is in between 11 % to 0.05 % as illustrated in table 3. While for the 80° configuration, the percentage of error of the measured reading is in between 42.85% to 2.24% deviation. The recommended incident angle is a near grazing angle about 76° to 84° to produce an accurate measurement. The experiment conducted at 78° shows a very low error with maximum error of 11.86 percent. At 80° the results have high percentage of error with the highest 42.85 %. With this result we can conclude that the optimal angle for the measuring device is 78° . Measurement on roughness more than $0.6\mu\text{m}$ is not accurate even though the wavelength of the laser used is 650 nm which is longer than the measured surface roughness. Shadowing and multiple scattering cause by surface irregularities of rougher surface than $0.4\ \mu\text{m}$ will result in some errors in recorded readings.

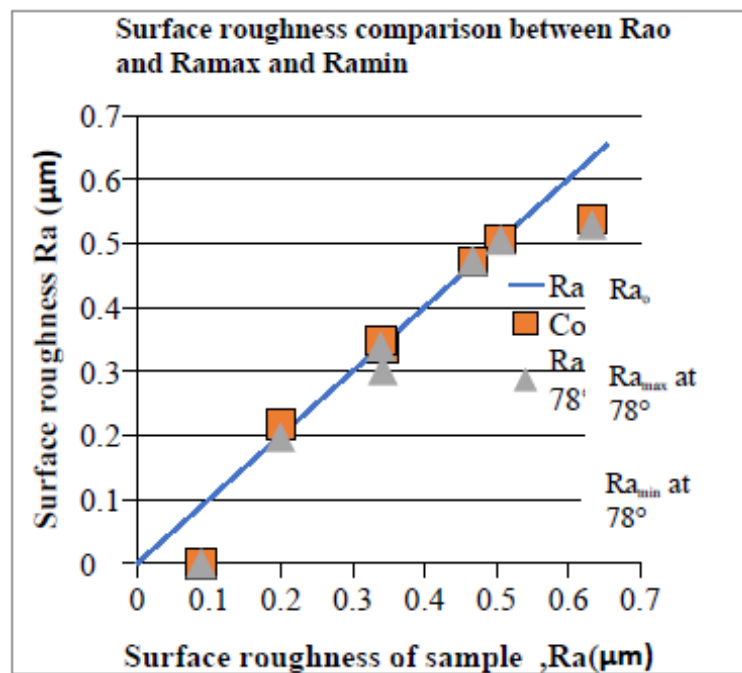


Figure 7. $R_{a_{\max}}$ and $R_{a_{\min}}$ measured by the non-contact measuring device compared to the measurement measured using mechanical stylus profilometer, R_{a_0} .

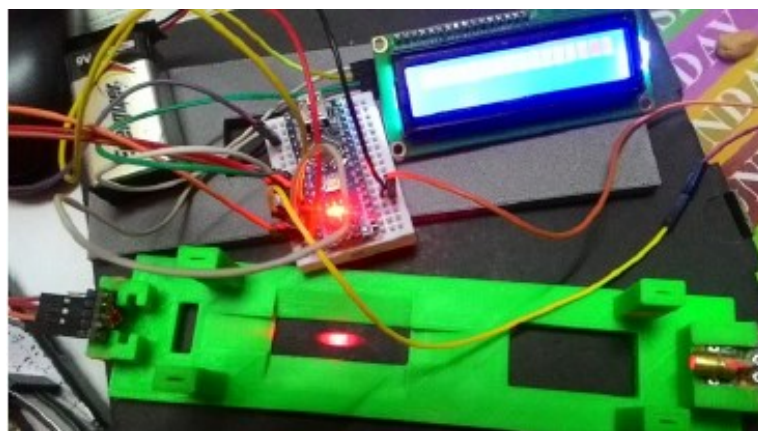


Figure 8: Components of the non-contact surface roughness measuring device

4. Conclusion

The work described here highlighted the contributions of a portable non-contact surface roughness measuring device in manufacturing process. Device operated by using optical method to measure the roughness values without any contact to the objects. Instead of using mechanical stylus profilometer as conventional method, non-contact method is able to avoid any scratch towards object surface during measurement process. As conclusion, the developed device is able to measure the roughness value with a slight error and the results are compared to the stylus profilometer device. This device is portable and capable to prevent scratch and damage in workpiece surfaces. Thus, it enhanced the measurement systems for any manufacturing applications.

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