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# MEASURING SURFACE PROFILE WITH LOW-RESOLUTION DISPLACEMENT LASER SENSORS

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*Abstract: A new application of laser displacement sensors in measuring surface texture has been reported from industry recently. To achieve high measurement precision, laser sensors with high-resolution, which are expensive and usually means high-laser-class, are required, because if low-resolution sensors are used, the surface signal could be hidden in the internal noise of the sensor. In this paper, the mean of a number (N) of measurements of a specific distance between the sensor and the measured point is used to better represent the distance and reduce the internal noise. An artificial neural network has been trained to estimate a suitable value of the number N for a predetermined measurement precision. This way the measurement precision can be dramatically improved whilst maintaining a suitable dynamic response. The method is then further developed for continuous surface profile measurement for in-process purposes. Studies on filtering different components of surface texture using Gaussian and triangle filters have been carried out. The filtering results can be used to evaluate surface finish parameters, such as roughness and waviness.*

*Keywords: Laser displacement sensor, surface profile, roughness, waviness, artificial neural network (ANN), filter*

## 1 INTRODUCTION

Optical techniques have great potential for in-process measurements of surface texture because of their high precision, non-contact, and high measurement speed. According to Vorburger et al [1], these techniques fall into two general classes: namely profiling and parametric techniques. Interferometry is an important profiling technique that has been investigated in some previous research, but the undesired features limit its applicability for in-process measurement [2]. There are some other optical methods relying on diffraction or scattering, but they can only yield limited information about the details of surface topography [2].

Triangulation displacement laser sensors have been used for measuring coarse surface texture (in the range of $R_a$ ³*10 mm*) [3]. Recently, much fine measuring results of using this technique have been reported from industry ($R_a$ in the range of *5.08 mm-126.9 mm*) [4]. Since the output voltages of the sensor are directly proportional to the distance between the sensor and the measured point, this new technique requires less calculation and analysis to evaluate surface finish parameters from the sensor outputs. Although the size of the laser spot will affect the horizontal measurement precision, with the rapid development of laser technology which constantly provides higher-resolution sensors with smaller laser spot and faster sampling frequencies, this new technique could be one of the most important techniques for in-process monitoring of surface finish.

Since high-resolution laser sensors are expensive, and usually employ high-laser-class resulting in more safety means required, it is worth of investigating the methods of using low-resolution sensors to conduct high precision measurements. For low-resolution triangulation displacement laser sensors, the main factor limiting their vertical resolution is their internal noise, which could hide the desired surface signal, therefore methods need to be developed to reduce this internal noise.

The obtained surface profile consists of three components: roughness, waviness, and form, which need to be separated with reliable filtering techniques for deriving the values of surface finish parameters. But the qualitative distinctions between these components can not be expressed as a certain number, because they depend on their relative spacing relationship [5]. Therefore, optimally, the cut-off wavelength for the filters should also be determined dynamically and relatively [6]. Conventional techniques of surface texture filtering, set 5 standard cut-off wavelengths--each of them covers a certain range of surface finish [7]. But this does not reflect the possibly large difference of the relationship of the surface texture components in the range that the cut-off frequency is applied.

## 2 SURFACE PROFILING WITH LOW-RESOLUTION LASER SENSORS

Many electronic systems generate random internal noise [8], so does the LA40HR laser sensor (vertical resolution 10 mV / *20 mm*) used in this research [9]. When measuring a fixed distance, the output voltage of the sensor will show variation due to the internal noise. To use a triangulation displacement laser sensor with low-resolution for surface profiling, two basic problems need to be solved: the reduction of the internal noise, and the implementation of the methods for the internal noise reduction in continuous measurements.

### 2.1 Internal noise reduction

Based on statistics, the following method suitable for in-process measurement has been proposed to successfully reduce the internal noise: (i) the sensor is constantly moving along the measured surface; (ii) meanwhile continuous measurement at a very high sampling frequency is performed; and (iii) the mean of *N* measurements that cover a very small sampling length ($L_m$) is calculated to represent the distance between the sensor and that part of surface [10]. When the number *N* is large enough, the random internal noise can be reduced to a certain degree to meet a required vertical precision, and the amount of noise remained in the mean is due to the statistical fluctuation and depends on the value of the number *N*.

Table 1 and Figure 1 demonstrate the non-linear relationship between the values of number *N* and the corresponding vertical measurement precision achieved in terms of standard deviation (*s*) of the output voltages. It is seen that when *N* increases from *1* to *2321*, *s* decreases dramatically from *10 mV* to *1mv*. Even *N = 10* will result in *s* decreasing from *10.0 mV* to *6.076 mV*. There is no significance in choosing a value of *N* larger than 2321, because the decrease of *s* is very limited.

**Table 1.** Calculation of standard deviation for given values of *N*

| N | 1 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 |
|---|---|---|---|---|---|---|---|---|---|
| σ (mv) | 10 | 0.608 | 0.599 | 0.541 | 0.525 | 0.492 | 0.462 | 0.440 | 0.425 |
| N | 90 | 100 | 200 | 300 | 400 | 500 | 700 | 800 | 900 |
| σ (mv) | 0.388 | 0.386 | 0.284 | 0.240 | 0.216 | 0.201 | 0.177 | 0.160 | 0.154 |
| N | 1000 | 2000 | 3000 | 4000 | 5000 | 6000 | 8000 | 10000 | |
| σ (mv) | 0.150 | 0.112 | 0.101 | 0.092 | 0.087 | 0.084 | 0.082 | 0.081 | |

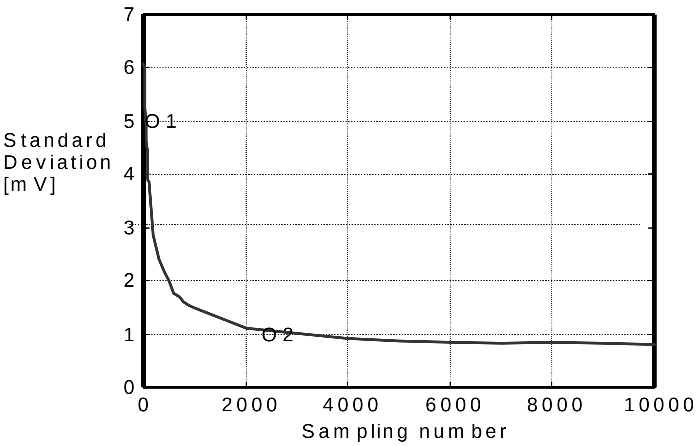



**Figure 1.** Relationship of sampling number *N* & measurement precision *s*

Theoretically, the vertical measurement precision with this method can be achieved as high as required by increasing the number *N*, but in practice, this is limited by the maximum sampling frequency of a sensor and the required sensor moving speed. Therefore, it is needed to calculate the values of number *N* for the predetermined precision requirements *s*. An artificial neural network (ANN) is easily designed with Matlab to solve this non-linear problem. The values of *s* and the values of *N* in Table 1 are used as the input-output training data pair, and the well trained ANN can then estimate the values of number $N$ to meet the predetermined vertical precision $s$. In Figure 1, the two points marked with 'O1' and 'O2' are the estimations of $N_1$ (=32) for $s$=5 mV and $N_2$ (=2321) for $s$=1 mV by using the well trained ANN.

In the horizontal direction, not only the laser spot size, but also the small sampling length $L_m$ that the $N$ measurements covers, will also affect the horizontal measurement precision, i.e. the smaller the $L_m$, the better the horizontal precision, but the slower the sensor moving speed. Therefore it is necessary to make a balance between $N$, the vertical precision $s$, the horizontal precision, and the sensor moving speed. In this research, the vertical precision is the main concern, and the experiment results suggest $L_m$ should be chosen within the range of ($D_0$/2--$D_0$) to make use of the maximum horizontal resolution of a sensor.

## 2.2 Application in surface profiling

The following procedures have been designed to perform surface profile measurement: (i) the measured workpiece is mounted on a CNC machine tool, (ii) the sensor is mounted on the cutting tool holder, (iii) as the sensor is moving along the measured surface with the cutting tool holder, continuous measurement is conducted to cover, say, 5mm measuring length, and (iV) the output data from the sensor is divided into some N-output sets, and the mean of each of the $N$-output is calculated to approximate the distance between the sensor and that part of surface. This way the internal noise contained in the output signal is reduced, and the measured surface is approximated with a number of steps, as the raw signal shown in Figure 2 in section 3.

It is possible to design a filter to remove the internal noise and get a reasonable result for each specific case. One difficulty encountered is that the cut off frequency of the internal noise could be close to the frequencies of surface roughness.

# 3 SURFACE TEXTURE FILTERING TECHNIQUES

Usually a surface profile consists of a range of frequency components: The high frequency components form the surface roughness, while surface waviness and form are compose of low frequency components. To separate the low frequency roughness and the high frequency waviness and form, suitable filtering techniques need to be applied, and reliable cut-off frequencies for the filters play a key role for the surface texture filtering.

## 3.1 Determination of the filters

The roughness average of the sample metal bars are measured with contact probe equipment, and used as a reference to verify the filters and the cut-off frequencies being used. Initially, a zero-phase forward and reverse digital low-pass filter was designed with Matlab to remove the low-frequency components from the raw data collected from the sample metal bars. Experiments conducted with this filter have shown that most of the roughness averages derived from the filtering results roughly meet their reference values. However, the roughest sample surface can not be determined accurately—its roughness average $R_a$ (=4.5 mm) is much less than its reference value ($R_a'$=9.3 mm). The reason is that not all the filters are capable of precisely separate surface texture components. Analysis shows that the failing of this filter is due to its bad performance of the around the sharp spikes and deep valleys in this roughest surface (intends to flatten the surface around these spikes and valleys).

Modern surface texture measuring techniques are turning to using some special filters, such as Gaussian filters and triangle filters. Equation 1 and equation 2 are the transfer functions for the Gaussian filter and the triangle filter respectively.

$$h(x) = \frac{1}{a \times l_c} \exp\left[ -p \left( \frac{x}{a \times l_c} \right) \right] \quad (1)$$

where $a = \sqrt{\ln 2 / p}$, $l_c = V / f_c$ is the cut-off wavelength ( $V$ is the relative moving speed of the sensor, $f_c$ the cut-off frequency), $x$ the position of the measured point on the surface.

$$h(x) = \frac{1}{B} - \left[ \frac{1}{B} \right]^2 |x| \quad (2)$$

where $B$ is the half-width of the base of the unit-area triangle, $x$ the position of the measured point.

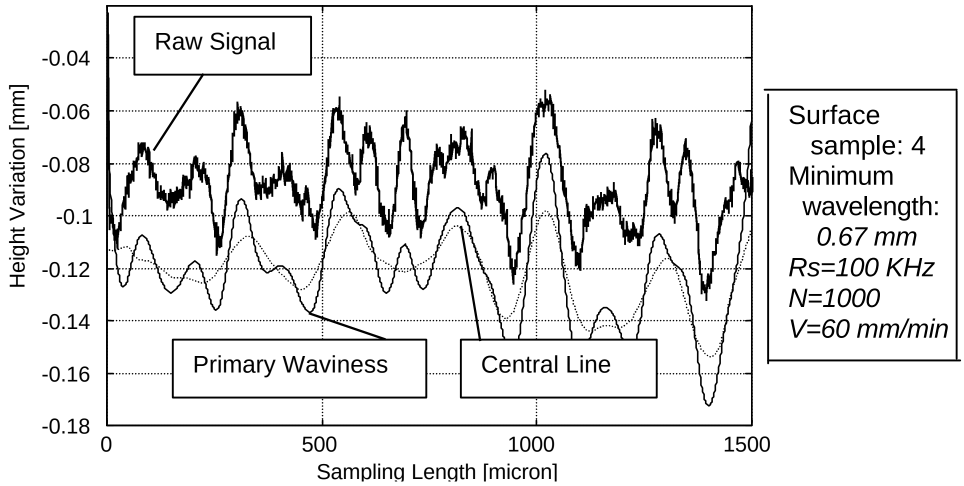
The Gaussian filter is designed to more precisely separate waviness from surface profile [10]. Its frequency response has a steep slope near the cut-off, so it is capable of more sharply distinguish the frequencies near the cut-off as either waviness or roughness. The triangle filter can be used as a computationally faster approximation of the Gaussian filter.

## 3.2 Determination of the dynamic cut-off wavelength

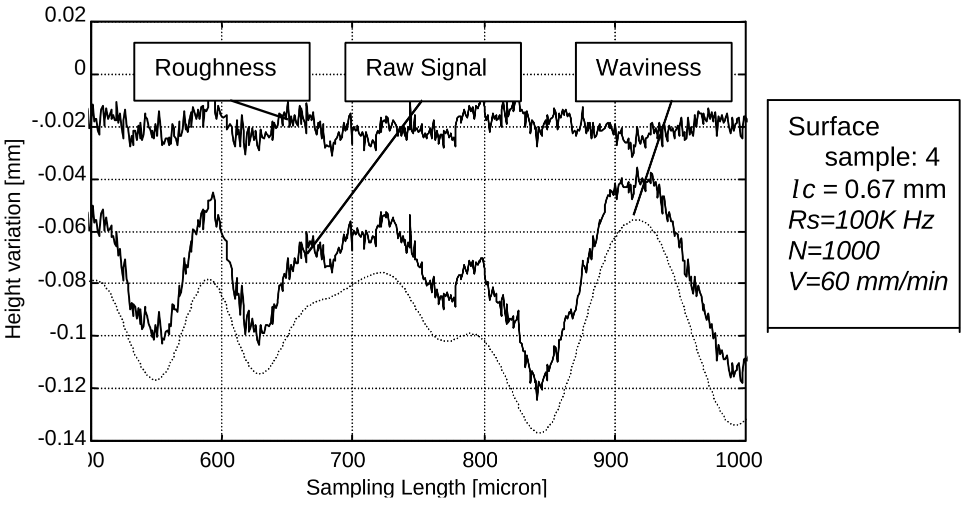
The cut-off wavelength specifies the wavelength bound below or above which the components are extracted or eliminated. Conventional techniques set 5 standard cut-off frequencies for different range of surface roughness average: *0.08 mm, 0.25 mm, 0.8 mm, 2.5 mm,* and *8.0 mm*. For example, $l_c$*=0.8 mm* is set for the range of *4.1 mm<*$R_a$*£203.2 mm* (for random surfaces). But one $l_c$ value is not flexible enough and cannot perform well in such a huge $R_a$ range. Instead, dynamic determination of the cut-off wavelength becomes necessary.

**Table 2.** Using of dynamic cut-off wavelength

| SAMPLES | SAMPLE 1 | SAMPLE 2 | SAMPLE 3 | SAMPLE4 |
|---|---|---|---|---|
| $\lambda_c$ (mm) | 0.59 | 0.89 | 0.64 | 0.67 |
| $R_a$' (refer µm) | 6.4 | 9.3 | 3.1 | 3.6 |
| $R_a$(µm) | 5.1 | 8.6 | 5.2 | 3.7 |




(a) Surface primary filtering with a triangle filter




(b) Surface texture filtering with Gaussian filters

**Figure 2.** Surface profiling and filtering

A triangle filter with standard cut-off wavelengths ($l_c$=*0.25 mm* for *2.0 µm*<$R_a$*£4.1 µm* and $l_c$=*0.8 mm* for *4.1 µm*<$R_a$*£203.2 µm* [7]) is used for pre-analysing the surface profile to produce primary waviness and roughness, a good approximation of Gaussian filtering. To estimate the dynamic cut-off wavelength, the primary waviness is divided by its central line--a curve on which each point has the average height of a number of points before and after the corresponding point on the primary waviness. Using this division, the minimum wavelength and some other parameters of the primary waviness is calculated.

The minimum wavelength obtained can be used as a better approximation of the cut-off. Figure 2 (a) and (b) demonstrate the surface profiling and filtering results for surface sample 4. The filtering is still not good enough as the dynamic cut-off wavelength could be estimated with a better solution, such as using an ANN. This part of research is still in progress.

## 4 CONCLUSION

This paper proposes methods to reduce the internal noise of triangulation displacement laser sensors, and therefore to improve the measurement precision significantly. The obtained surface profiles are pre-processed with a triangle filter for dynamically estimating the cut-off wavelength used in the Gaussian filter to more precisely perform the separation of surface waviness and roughness.

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