Limitation of a Line-of-Light Online Paper Surface Measurement System

Anzar Alam, Mattias O’Nils, Anatoliy Manuilskiy, Jan Thim, and Christina Westerlind

Abstract—A new prototype device has been developed based on a laser triangulation principle to measure online surface topography in the paper and paperboard industries. It characterizes the surface in a wide spatial scale of topography from 0.09–10 mm. The prototype’s technique projects a narrow line-of-light perpendicularly onto the moving paper-Web surface and scattered reflected light is collected at a low angle, low specular, and reduced coherent length onto the CCD sensors synchronized with the laser sources. The scattering phenomenon determines surface deviations in the z-direction. The full-width, at half-maximum of a laser line in cross section is sensitive in computation of the surface topography. The signal processing aspect of the image processing, for example, threshold and filtering algorithms are also sensitive in estimating the accurate surface features. Moreover, improper light illumination, intensity, reflection, occlusion, surface motion, and noise in the imaging sensor, and so forth, all contribute to deteriorate the measurements. Optical techniques measure the surface indirectly and, in general, an evaluation of the performance and the limitations of the technique are both essential and challenging. The paper describes the accuracy, uncertainty, and limitations of the developed technique in the raw profiles and in terms of the rms roughness. The achieved image subpixel resolution is 0.01 times a pixel. Statistically estimated uncertainty ($\sigma$) in the laboratory environment was found 0.05 $\mu$m for a smooth sample, which provides a 95% confidence level in the rms roughness results. The depth of field of the prototype is $\sim$2.4 mm.

Index Terms—Laser triangulation, optical profiler, online surface measurement, limitation, uncertainty, accuracy, calibration, paper-web topography.

I. INTRODUCTION

SURFACE quality, in general, is of significant importance within the aerospace field, medical field, bioengineering, geomorphometry and tribology. Papers are required to be manufactured with a high print quality, high brightness and high glossiness and homogeneous in terms of surface topography. The smooth and uniform surface improves the surface’s perceived quality, runability and, additionally, reduces the amount of coating and consumption of ink during printing. Because of the significance of the surface topography, the online surface metrology subsequently demands both accuracy and reliability of the measurement technique.

Surface measurement of an engineering product during the manufacturing process, under undefined dynamic conditions, is a challenge, particularly within the paper and paperboard industries. There are a number of laboratory instruments, which are available, including contact and non-contact with vertical and lateral resolution up to 1 mm and 1 $\mu$m, respectively, with high accuracy and high gauge repeatability and reproducibility (GRR). An optical system is fast in comparison to that of the contact based instrument but, at the same time, an optical system has a tendency to produce errors based on internal and external noises in the system. Internal noise refers to the noise in the imaging sensors and external noise mainly refers to the noise due to surrounding and the ambient conditions, for example, ambient light and vibration in the machines that can vary with time. The presence of noise in the measurement data exaggerates the surface roughness reading and, despite the increasing application of laser based metrology, a laser measurement is less accurate in comparison to that of a contact based instrument [1]–[4]. The majority of the recent research work has been focused on the development and application of the laser system, while less work has been involved in analyzing the error sources and the uncertainty of the laser based measurement [5]. Analysis of the optical and imaging system’s accuracy is comparatively challenging and is important in order to achieve a quantitative control with regards to the uncertainties that a real time continuous processing system introduces into the measurement results [6]. The challenge is particularly true if the measurements are to be conducted at high speed and in a harsh industrial environment. For example, in the paper and paperboard manufacturing floor there could be a number of sources of errors, such as; vibrations, a rough industrial environment and the dynamically varying behavior of the machines and, in addition, the properties of the paper surface itself. It is essential for an effective and fine calibration of the optical setup to be conducted periodically in order to reduce any internal error in the measuring system. Online profilers are supposed to be fast, robust, and capable of measuring a wide range of roughness with high accuracy. We have developed a prototype device based on a laser line scanning technique, which will subsequently be called “prototype”. The advantages of laser line scanning over tactile based measurements are that it scans the surface in a single step, resulting in a simpler and
significantly faster measurement probe. However, the laser line scanner suffers from occlusion, high influence from color, glossiness, transparency and other surface properties [1] that contribute to a reduced accuracy. Measurement errors could be caused by the hardware, software, improper machine adjustment, filter and ambient conditions. In relation to analyzing the surface profile, a key part is the choice of filtration and its configuration. It not only requires knowledge of the detailed behavior of the filter algorithm but, additionally, knowledge regarding the paper surface, which is being measured. The filter should be robust against outliers, valid for the complex geometry of the surface and reliable for the entire range of the measured data [7]. Paper surface properties lie within a wide scale of spatial wavelengths, which makes the surface more complex and the features, such as roughness and waviness, possess no standardized definition. This non-standardization is in context to paper and paperboard. Because the paper and paperboard surface features vary as per the type and quality of the paper. The roughness and waviness definition changes as per the paper type and these definitions also vary from one manufacturer to other manufacturer. For example, a photographic paper surface could have a shorter wavelength range to define roughness whereas, for a general purpose paper, its range could be wider. Alternatively, some features may be treated as roughness in one application and the same features could be termed as waviness in other application [8].

Based on continuous enhancements, regarding quality paper production, a higher accuracy in the measurement devices with a higher resolution and proven reliability is thus required. Therefore, it is essential to identify the sources of errors in the measurement system. The prototype device was installed and tested in the paper and paperboard manufacturing industries in Sweden. This article describes noise, accuracy and the uncertainty budget of the developed prototype. This article can be treated as an extension of the published article [9].

II. ACCURACY: PRE-DESIGN CONSIDERATIONS

A. The Direction of Measurement in the Paper Mill

The paper surface can be scanned either in the machine direction (MD) or in the cross direction (CD) as illustrated in Fig. 1.

A separate study was conducted in order to investigate the topographical differences in the MD and CD and it was concluded that higher topographical features can be measured in the CD than in the MD [10]. However, manufacturers also require measurements in the CD as it is necessary to have information regarding the roughness across the width of the paper-web as this is important for the quality of the produced paper.

There are three well known techniques to scan a surface; point, line and area [9]. In this case, a line scanning technique is adopted in order to meet the fast measurement requirement and to enable measurements to be taken in the CD.

B. Prototype Installation Location

The prototype was intended to be installed at a location on the paper-web where measurements of surface roughness could be both accurate and reliable. As an example, in Fig. 2(a) two possible different locations are shown at which measurements can be taken. In location 1, there is a rolling cylinder behind the moving paper, which makes the paper surface stable, smooth and free of wrinkles with a reduced vibration effect. Location 2, on the other hand, is similar to a free hanging paper surface and, carries significant shrinkages due to tensions, which can cause variations in the long waviness on the paper surface, these do not actually reflect the true paper surface properties and, there is no intention within this study for these to be measured. The appearance of these shrinkages and long waviness at location 2 caused it to become difficult to measure the true roughness of the surface and, in addition, caused sources of error in the optical system due to improper line focus, occlusion, spreading of laser line, etc. leading to a complete failure of measurements. Therefore, in order to minimize the errors in the measuring system, the decision was taken for the installation of the prototype to be at location 1 or somewhere similar.

Furthermore, the dynamic abnormal change of process speed could exert tensions, as well as relief, on the paper-web against roll. The relief case is depicted in Fig. 2(b), in which wrinkles on the loose paper surface could easily cause there to be misinterpretations with regards to the measurement. It is observed that a thick paper, for example, paperboard as shown in Fig. 2(c) does not suffer significantly from shrinkages and wrinkles, and therefore, in such situations, measurement can be obtained in a straightforward manner. However, in relation to lightweight paper and light weight coated paper (LWC), there is the possibility, on rare and, often, brief occasions, in which the measurement can be influenced by wrinkles or long waviness on the paper-web. These situations are eradicated by the designed software, which simply omits such measurements. The prototype installation at a pilot coater machine is shown in Fig. 2(d) [11].

III. ACCURACY: EXPERIMENTAL ESTIMATION

A. Sub Pixel Resolution, COG and Line-of-Light FWHM

The prototype projects a narrow line-of-light onto the moving paper-web and is captured by the industrial CCD imaging sensors, obliquely, at a low specular angle with a spatial resolution of 44 μm along the line-of-light. The use of low specular light assists in avoiding saturation of the pixel intensity, which is possible in cases involving a very smooth surface. The oblique light covers a wide scale of the surface features to be captured. The detail of the technique has been described in [9].

The line-of-light image, as shown in Fig. 3(a), has a resolution of 1600 × 40 pixels. The center of gravity (COG) of the
Fig. 2. Illustration of laser line scanning locations onto a moving paper-web. (a) Indicates two possible locations, location 1 (wrinkle free) and 2 (with wrinkle). (b) Long waviness and loose paper against rolling cylinder. (c) An ideally smooth paper-web. (d) Prototype installation against moving cylinder at pilot coater machine.

image is calculated columnwise and the image is transformed into a one dimensional array of size 1600. The paper surface topography is estimated by calculating the relative position shift in the COG in the image. The accurate estimation of the surface features is highly dependent on the accuracy of the COG. A magnified part of the image is shown in (a) along with the cross-sectional width of the line. The line’s full width at half maximum (FWHM) is about 2-3 pixels, which plays an important role in the accuracy of the COG. The system’s resolution, accuracy and noise depend on the FWHM. A FWHM wider than 2-3 pixels will reduce the sensitivity in the COG and, if it is shorter, it will increase the sensitivity; however, this will simultaneously increase the noise, as shown in Fig. 3(b).

The accuracy of the COG depends on the width of the line-of-light and also on the subpixel resolution of the imaging sensor. A subpixel resolution of the image of 0.1 times is reported in the literature [12], [13], however, this prototype achieves an image subpixel resolution of 0.01 times, or, equal to 0.44 μm. To achieve an accurate COG position by means of a subpixel resolution, it is essential that the COG standard deviation, caused by the width of the line, is significantly less than the system noise. Fig. 3(b) is a plot obtained by a theoretical model, developed in house, which represents the relationship between the FWHM of a line-of-light and the COG’s standard deviations in the line-of-light, as noise. It shows a higher noise if the line-of-light FWHM is equal to or less than 1 pixel. The conclusion drawn is that the minimum FWHM, with regards to the line-of-light image, must be larger than one pixel in order to maintain accuracy. The width of the line-of-light in the prototype is maintained at 2-3 pixels for two main reasons.

One is that a line wider than 2-3 pixels could cause the COG to be less sensitive to extract surface features and the other is that if it is less than 2-3 pixels, the noise in the COG will increase, thus an FWHM of 2-3 pixels is optimum.

B. Surface Fibers Orientation and Effect on Line’s FWHM

Paper possesses a complex surface geometrical structure and in general, the paper surface fibers align in every direction around 360°. However, it is known that the majority of the
fibers during the manufacturing process become aligned in the machine traveling direction, namely the MD. The investigation studies show that there is only a minor topographical difference between the measurement in the CD and MD and, if the surface is very smooth, then there is no significant difference between the two [10]. The conclusion is that the fibers on the paper surface are generally aligned in both the CD and in the MD with only minor differences. However, some fibers also become aligned in between the CD and MD. In a broad sense it can be stated that surface topography features exist in the spatial wavelength $\lambda$, whose direction could be anywhere within the $360^\circ$, however, the majority of $\lambda$ has its direction in either the MD and CD as wavelengths $\lambda_{MD}$ and $\lambda_{CD}$, respectively. In other words, when a line-of-light is projected onto the moving paper-web it carries information of the surface features in the wavelength $\lambda$ and the Fourier spectrum of the surface features will decompose its components in the $360^\circ$, the majority of whose components exist in the MD and CD. For example, if the surface features are aligned in between the MD and CD then the surface spectral data will contain frequencies in both the CD and MD.

A paper surface in Fig. 4 represents surface features in two directions, the black parallel lines show spatial wavefronts when the fibres are aligned in the MD and the red parallel lines represent spatial wavefronts when the fibres are aligned in between the MD and CD. The first discussion is in relation to the case when the fibres are aligned in the MD, therefore, the other component $\lambda_{MD}$ will be longer than the $\lambda_{CD}$, and thus line-of-light FWHM will face any resolution problems and no sensitivity problem will exist in relation to calculating the COG. In the second case, the red parallel lines represent the surface wavefronts in the cross direction. In a similar manner, the surface wavefront is again represented by the wavelength $\lambda$ and by both its component $\lambda_{CD}$ and $\lambda_{MD}$. As shown in Fig. 4, the component $\lambda_{CD}$ will behave in exactly the same manner to that of the first case, however, the wavelength of the component $\lambda_{MD}$ could potentially be shorter than $\lambda_{CD}$ and thus, the line-of-light FWHM will suffer from a resolution problem because it is unable to extract the finer features of the surface and will contribute to the poor sensitivity of the COG.

It is concluded that the COG is sensitive to the width of the laser line and, as long as the width of the laser line is shorter than the wavelength components $\lambda_{CD}$ and $\lambda_{MD}$, the surface features can be measured without any resolution problems. Thus the COG is sensitive to the angle of the direction of the fibres, however, this will not have a significant effect on the result in the measurement error as, and the majority of the fibres during the manufacturing process are aligned in the CD and MD.

C. Accuracy and Calibration in the z-Direction

The surface z-directional (out-of-plane) accuracy test was performed by using a linear translation, having a resolution of $1.25 \, \mu m$. A mechanical setup, which consists of a linear translational device shown in Fig. 5(a), was mounted on top of the prototype in order to measure the surface height of a photographic paper sample with an evaluation length of 20 mm. After an initial adjustment to the prototype, the sample surface was managed so that it was able to lift $\Delta h \, \mu m$ along
Fig. 5. Experimental test to record surface height change and corresponding change in a pixel of the line-of-light onto the imaging sensor from 0 to 7.5 μm. (a) Mechanical setup using a linear translation. (b) Illustration of the technique. (c) Plot; mechanical height change Δh on vertical axis and corresponding shift in pixel position Δz on horizontal axis.

The vertical direction, in discrete steps of 1.25 μm from a reference position to 7.5 μm. The prototype device projects a laser light onto the paper surface and the reflected light is recorded by the CCD sensor as depicted in Fig. 5(b).

The linear translation moves the paper surface in the vertical direction, which causes the Δz position shift of the line image onto the CCD sensor. The change in height was conducted in discrete steps and the corresponding shift of the pixel position onto the CCD sensor was recorded.

Fig. 5(c) is a plot which shows the mechanical height change on the vertical axis and the corresponding position shift of the pixel on the horizontal axis. A linear trend line is also shown in the plot, which predicts the regression $R^2$ to be 0.99.

The paper sample height change of 7.5 μm resulted in an average pixel shift of 0.290 and the conclusion is that, on average, a shift of 1 pixel onto the imaging sensor corresponds to, approximately, a shift of 43.25 μm in the surface height. Thus, in the computation algorithm, each pixel in the COG is multiplied by a calibration constant of 43.25 to obtain a real world scale in μm.

D. Measurement Accuracy

To compare and estimate the accuracy with regards to the surface height (z-direction) measurement of the developed device, a high resolution industrial researched based profiler FRT MicroProf was used in this experimental work as a reference device. FRT MicroProf claims, 10 nm z-direction accuracy, a spot size of 1 μm and is configured with 20 μm resolution along the line-of-light. A specimen of a paperboard that possesses scratches on its surface was chosen to be measured with regards to its height variation on the surface.

Two fixed dots were marked across the three scratches, as reference points, so that each time a measurement is made, exactly the same line is made by both the FRT and the prototype. A line joining two marks, over the scratch surface, was scanned 11 times by the FRT profiler and by the prototype and the average profile is drawn in Fig. 6.

There are three distinct valleys in each of the plots. Plot (a) is obtained by the FRT profiler and (b) by the prototype. In order to avoid traceability problem in two figures 6(a) and (b) the differences of height from valley 1 to 2, 2 to 3 and 3 to 1 were taken for each plot. The reason behind is that it was difficult to trace exactly the same point on the two plots and the two plots were obtained from two different devices operating on different techniques and resolution. The depth differences in the three valleys in each of the plots were calculated by both the FRT and prototype, as entered in 2nd and 3rd column of Table I, respectively. The last column shows
TABLE I
MEASUREMENT DIFFERENCES BETWEEN FRT AND PROTOTYPE FOR A SCRATCH SAMPLE

<table>
<thead>
<tr>
<th>Difference of height from</th>
<th>Measured by FRT (μm)</th>
<th>Measured by prototype (μm)</th>
<th>Full scale % difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valley 1 to 2</td>
<td>5.64</td>
<td>4.58</td>
<td>2.67%</td>
</tr>
<tr>
<td>Valley 2 to 3</td>
<td>21.93</td>
<td>20.21</td>
<td>4.31%</td>
</tr>
<tr>
<td>Valley 3 to 1</td>
<td>16.29</td>
<td>15.63</td>
<td>1.65%</td>
</tr>
</tbody>
</table>

the valley height difference between two devices in percentage terms. The full scale variation is considered to be 40 μm in both measurements and, accordingly, the full scale difference between the two devices was found to be 2.67%, 4.31% and 1.65%. This means that, if the surface height is 1 μm, there would be a difference of 0.026 μm between the valleys 1 and 2. It is important to mention that these differences are based on laboratory measurements, which are expected to be high for the online measurements on the manufacturing floor.

E. Accuracy and Correlation in the rms Roughness

The paper surface quality is measured in terms of average roughness and, additionally, as the root mean squared roughness $R_q$, which is a function of the surface profile deviations from a mean line [14], [15]. This section estimates the accuracy and correlation of a sample in rms roughness $R_q$ measured by the prototype and the reference device. In this study the spatial long wavelength cutoff was set greater than 8.75 mm and the short wavelength cutoff was set to less than 0.09 mm. Therefore, the rms roughness $R_q$ was estimated for the surface features which lie within the spatial wavelength ranging from 0.09 mm to 8.75 mm.

The papers are manufactured for a wide scale of surface qualities from coarse to multilayered coated smooth paperboard; therefore, the online measurement technique should be both capable and be proven to measure accurately within this wide scale. In the previous section, the prototype accuracy was estimated in a straightforward manner in the profile height without applying any signal processing. To determine the accuracy of the prototype profiler in the rms roughness, a reference paper sample is required whose surface roughness is less than any paper surface which is to be produced in the paper mill. For this purpose, a high quality paper Canon, Pro Platinum, PT-101, 300g/m² was taken as a reference sample.

This pro platinum photographic sample was scanned at 11 different locations, in sequence, having an evaluation length of 70 mm, both by the FRT and the prototype as shown in Fig. 7. Furthermore, at each location, the surface was scanned 11 times, repeatedly, retaining the same conditions, in order to evaluate the average roughness data $R_{q1}$. In this manner, 11 roughness values $R_{q1}$ to $R_{q11}$ were also obtained for locations 1 to 11, respectively. The FRT had scanned the surface 11 times in sequence, each at a distance of $Δx = 20$ μm. Similarly, the prototype had also scanned the same sample 11 times but, in this case, each was at a distance of $Δx$ greater than 20 μm, covering a range of 1-2 mm in total. The roughness for all 11 locations, i.e. $R_{q1}$ to $R_{q11}$ is plotted in the scattered plot Fig. 8.

In addition to the i) photographic paper sample, described above, three more paper samples ii) coated paperboard, iii) lightweight coated paper and iv) base paperboard were measured a number of times for rms roughness by the FRT profiler and by the developed prototype. Figure shows correlation among these four groups of samples $R_q$ measurements [15].
these are plotted in Fig 8. The plot is in a logarithmic scale and shows a reasonable correlation among the four groups of surfaces by these two devices.

It can be seen that some measurements do not correlate well between the two devices. This could be caused by many reasons including resolution, different cut-off wavelengths, different measurement techniques, etc. For example, the FRT has a higher resolution ($10 \ \mu m$) than the prototype with its lower resolution of ($44 \ \mu m$) along the line-of-light, furthermore, the FRT uses a kind of vacuum table, which causes a reduction in the long spatial wavelengths amplitude on the paper surface.

Similar correlation plots for the newspaper and cardboard surface, measured by the prototype and by the industrial Sture-3 profiler, have also been previously presented in the article [15].

IV. MEASUREMENT UNCERTAINTY

The ISO standard 14253 “Guide to the estimation of uncertainty in measurement” in brief, GUM provides guidance for industry with regards to the measurements and calibration of the instruments used in geometrical product specifications. The guide recognizes that the measurements should be expressed by means of the uncertainty instead of errors. Systematic sources of uncertainty can be minimized by schedule calibration of the measurement system because it is time dependent. However, we have focused in this article to estimate uncertainties in the random error and it is usually estimated by calculating the standard deviation from repeated measurements. The uncertainty displays a range of doubt, which could exist around a measurement result.

A. Uncertainty in the Profile

The steps described in Fig. 7 were actually applied to the two paper samples, namely the photographic paper and the coated cardboard so as to obtain the standard deviations from the average profile data $Prof_{\sigma 1}$ to $Prof_{\sigma 11}$, after which the average of these 11 standard deviations was determined as $Prof_{\sigma}$. These were determined as 0.43 $\mu m$ and 0.34 $\mu m$ for the photographic paper sample and the coated cardboard, respectively. The standard uncertainty $u$ can be calculated by means of by (1) [16],

$$u = s/\sqrt{n}$$  

where, $s$ is the standard deviation ($Prof_{\sigma}$) of a set of measurements and $n$ is the number of repeated measurements in the set. In our case, the number of measurements in a set is 11. The standard uncertainty $u$ is determined as being 0.130 $\mu m$ for the photographic paper and 0.102 $\mu m$ for the coated cardboard.

B. Uncertainty in the rms Roughness Data

Referring to Fig. 7 once again, the standard deviations estimated in relation to the rms roughness data are described as $Rq_{\sigma 1}$ to $Rq_{\sigma 11}$ for the locations 1 to 11. The $Rq_{\sigma 1}$ to $Rq_{\sigma 11}$ were calculated for the samples of photographic paper and the coated cardboard and plotted in Fig. 9 in random sequence. This plot provides a graphical presentation, thus enabling observations regarding the variations to be made with regards to all 11 standard deviations for both these samples. Generally, $2\sigma$ is accepted in order to provide a 95% level of confidence in the measurement results. Table II lists the minimum, maximum, average and 2 $\sigma$ uncertainty in $\mu m$. The $2\sigma$ values, 49 nm and 37 nm for the photographic paper and the coated cardboard samples, respectively, estimates a 95% level of confidence in the measurement system.

It is noted, from the previous section, that the uncertainty in the profile is significantly higher than the uncertainty found in the rms roughness. The fact is that the profiles are raw data, which contain all the components of the surface geometrical features, whereas, the roughness data are extracted after signal processing and the application of the filter. Because $Rq$ is calculated in the limited range of wavelength (0.09 mm to 0.875 mm) and the rest of the wavelength components are discarded. Thus only a part of the original noise is propagated while calculating $Rq$.

C. How Many Data Needed to Present Final Average Result?

A single roughness value is not sufficient to characterize the surface during the online measurement. It is necessary to present the final result by averaging a number of individual $Rq$ values, which enables the smoothing of the result and also minimizes the error. Averaging a large number of values also reduces the resolution of the measurement in the machine direction. The prototype is capable of measuring every meter on the paper-web and, if the final result is presented from the average of 10 $Rq$ values, it means that a result is given

![Graphical representation of standard deviations for the set of rms roughness data (Rq_1 to Rq_11) plotted for: i) Graphic paper and ii) Coated cardboard samples. Each $\sigma$ is calculated among the 11 repeat measurements to estimate uncertainty in the prototype device.](image)
every 10 meters along the MD. It is a trade-off between the measurement uncertainty and the resolution along the MD. The question then remains regarding the amount of data that should be averaged in order to obtain a reliable measurement during online. To predict an answer a fine photographic paper sample was repeatedly measured for rms roughness $R_q$ 100 times in a fixed location, while retaining identical laboratory conditions. Following this, the sequential averages of 10 $R_q$ were calculated from the 100 $R_q$ values. Thus, by this means, 10 sets of average values were obtained, each having 10 $R_q$. The standard deviation was determined from the 10 sets of $R_q$ and the maximum was found to be 0.048 $\mu$m, which is rounded to 0.05 $\mu$m. The standard uncertainty $u$ is re-written to determine the number of averages $n$ as shown in Eq. (2). Substituting $s = 0.05\mu$m and iterating using $u = 0.005$ to 0.05 $\mu$m, the plot of Fig. 10 is obtained.

$$n = \left(\frac{s}{u}\right)^2$$  

A straight line with constant value of $s = 0.05\mu$m is also plotted in Fig. 10 for the comparison purpose.

The online measurements during the manufacturing process suffer from electronic and process noise in addition to process variations, which could introduce error into the overall measurements. Therefore, the final result should be presented by averaging a number of individual $R_q$, with reduced noise. The optimum number regarding the average for the online measurements is chosen to be 10 for this application in order to confidently characterize the surface. If the value is greater than 10, this will only slightly improve the accuracy but, at the cost of MD resolution.

**D. Prototype Depth of Field (DOF)**

Depth of Field (DOF) is an important parameter for any optical technique. It defines the range of heights along the optical axis, on either side of the focus point, which remains in acceptable focus [17]. The prototype is designed to measure the paper surface against the paper-web. Once the line-of-light is tuned and focused onto the paper-web surface, the measurements remain stable as long as the optics remains within an acceptable range of focus. It was described in section IIB that the paper-web suffers from vibrations, waviness and shrinkages, which could lead to a change in the surface height, consequently making the line-of-light to become unfocused. Therefore, it is essential to know the range for the height change of the object, which still enables the measurements to remain stable and accurate within a tolerable range.

To estimate the DOF of the prototype, a photographic paper sample with an evaluation length of 18 mm was taken as an object and the line-of-light was focused on its surface. This sample surface was simultaneously measured for the change in $R_q$ roughness values, while changing its vertical position by a total of 6.4 mm as depicted in Fig. 11(a). The value of $R_q$ was plotted in Fig. 11(b) while initiating the move of the paper sample vertically up from the lower position $\Delta z_{Down}$ to the $\Delta z_{Up}$. The plot shows three regions, as marked by the double arrows, the first and the last are considered as being out of range, alternatively out of the focus region, because in these areas a slight change in the vertical shift of the sample causes a greater change in the roughness result, which will definitely lead to errors in the system. The middle region, the operating range, indicates the depth of field (DOF) of the prototype technique, which is about 2.4 mm from the center of the focus. The standard deviation in the roughness values at this DOF region is found to be 0.0357 $\mu$m, while the $2\sigma$ is 0.071 $\mu$m, which provides a 95% level of confidence in the measured data. The typical range of surface roughness for the online measurements is from 0.5 to 15 $\mu$m, therefore, 2.4 mm DOF is satisfactory for the online measurements; however, beyond this DOF limit,
the measurements are unreliable and exaggerated. The 2.4 mm estimated DOF may vary depending upon the type of the paper and their application, that is, this range could be longer or shorter, and the shorter will further improve the accuracy.

V. CONCLUSION

It is explained in section II that the prototype is designed to measure against the metal cylinder, which is the stable location, where the waviness on the paper surface is minimum. The prototype technique’s limitation is that the cylinder vibrations, in combination with any unforeseen waviness on the surface, must not cause the paper-web surface position to deviate beyond 2.4 mm as it will be out of the DOF range of the prototype.

The imaging sensors used have 1600 pixels along the line of measurement in order to capture the 70 mm length of paper surface, which means 1 pixel represents 44 μm on the paper surface along the line-of-light. This is a trade-off between the resolution of the device and the cost. The higher resolution of the imaging sensor will increase the accuracy and enhance the capability of the measurement system.

The line-of-light limitation in terms of the spectral width of the line is discussed and the optimum width of the line-of-light is estimated 2-3 pixels.

The COG of the captured laser line-of-light image is sensitive to the direction of the fibers. The prototype measures in the CD that is laser line remains perpendicular to the majority of the fibers that are aligned in the MD and in this case width of the line-of-light will not have any resolution problem. However, some fibers can align in between the CD and MD, under this conditions the width of the line could suffer resolution problem if it is longer than the surface features either in the λCD and/or λMD.

The core of the signal-processing aspects of the image-processing is the image COG. The image subpixel resolution is 0.01 times of a pixel. A paper sample height was mechanically modulated up to 7.5 μm and it was found correlating with the position change of a pixel onto the imaging sensor. Another paper specimen with maximum z-direction height deviation of 40 μm was measured by developed prototype and a reference device. The difference between these two measurements was found 2.88%. The rms roughness measured on a number of different grades of paper samples were found in correlation with the reference instrument. The standard uncertainty in raw profile using 11 numbers of measurements estimated 0.130 μm for the photographic paper sample. The statistically estimated uncertainty (2σ) in the laboratory environment was found 0.048 μm for a smooth sample, which provides a 95% level of confidence in the measurement results. The prototype scans the surface at every meter along the machine directions; however, resolution in the MD reduces by averaging the number of individual results in order to reduce the noise in the final measurements.

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REFERENCES


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