# Statistical Surface Analysis as a High Speed Process

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*Abstract:-* In the course of an industrial research project a high-speed optical surface defect detection system was developed. The material to inspect is piston ring wire. Main condition was to continuously inspect the whole surface without slowing down the production speed of 0.5 to 1.5 meters per second. The minimum defect size was defined by 100 µm extension in one dimension at wire perimeters up to 40 millimeters. This leads to an amount of up to 120 megabyte of image data to acquire and process in a second. To meet this requirements on one hand fast hardware components (cameras, frame grabber) had to be utilized for grabbing the image data. On the other hand high-speed image processing algorithms had to be developed to compute features which can indicate defects out of the image data. The developed image processing algorithm is based on the computation of higher statistical moments, which turned out to be well suitable to distinguish between the gaussian distribution of the image data from faultless surface and disturbed statistical distributions in the presence of defects. The adaptation of this concept to line scan image data and the implementation on on-board processors necessitates some modifications, which result in increasing processing speed, better localization of the defects and higher sensitivity.

*Keywords:-* Surface inspection, high speed processing, central moments, kurtosis, linear filtering.

## 1 Introduction

In the production of continuous material there is a rapid growing need of a hundred percent quality control to meet the high demands of new quality standards and therefore to remain competitive. An additional requirement is not to slow down the production process caused by the examination. Classical inspection methods often choose statistical representative sample sets and/or examine off line. This is not feasible in all cases and far away from a 100 percent inspection. Newer contact free techniques, to mention eddy current methods in steel industry as an example, already cover some areas of continuous one hundred percent examination. These methods are in principle capable to detect very small defects, if they have a certain depth extension and they perform also at high production speeds.

Optical methods with sequencing image processing cover a wider field of application. One of their crucial questions is if the image processing speed matches the production speed so that 100% surface inspection is guaranteed.

## 2 Problem Statement and Hardware Solution

The presented study treats with piston ring wire at production speeds between 0.5 and 1.5 m/s. Surface defects with a minimum size of 100 µm have to be detected. The perimeter of the rectangular cross section of the wire reaches up to 40 millimeters. (Fig.1). Considering Shannons sampling theorem a first rough calculation leads to a maximum data throughput of 120 megapixel per second. This is equivalent to about 120 megabyte per second if 8 bit grey level resolution and a 4x1024 pixel scanning line is assumed (four cameras). This is at the upper performance limit of recent frame grabbers. One not only has to grab the data but also process it for detecting the defects in real-time. To reach such high grabbing and processing speeds, a grabber with on board DSPs and an additional processor board linked via a direct data bus module was chosen. The digitizer unit consists of four digital 1024-pixel line scan cameras - one for each side. Their signal is synchronized and combined to one digital grabber input signal via a synchronization unit. The extremely short integration times (according to line scan frequencies up to 30.000 per second) necessitate a powerful halogen cold light illumination led to the object surface through fiber optics. The illumination benefits from the metallic reflecting property of the material - which allows increasing the efficiency by acquiring the data in direct reflecting light. The advantage of line scanning is that one has to adjust the optical and illumination parameters only along a line, which results in uniform focus and light behavior in the direction of movement. This solution is implemented in a prototype, which was going on line at the beginning of 2002.

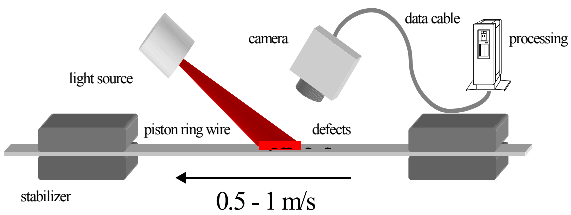


**Figure1:** Principle of hardware solution.

## 3 Processing Algorithm

During the first feasibility studies the data representation in sample images of typical defects has been analyzed regarding signal shape, signal to noise ratio and statistical properties. It arised that the grey levels of the defect free surface are well gaussian distributed (Fig.2). This was crucial to the further search for a suitable detection algorithm capable to detect a wide spectrum of defect types of even low contrast.

Several algorithms have been adapted and tested including thresholding with neighborhood condition, co-occurrence and correlation analysis, linear filtering, blob analysis, watershed transformation and calculation of statistical moments. A very selective error parameter group proved to be one based on calculating higher statistical moments. These statistical measures make impact on different fields of image analysis, to mention multiscale statistics [1] or non-linear diffusion [2]. Moreover the concept was established in some less time-critical applications, within several feature extraction and classification studies in the field of defect detection on metallic surfaces [4], [5], [6], [7].

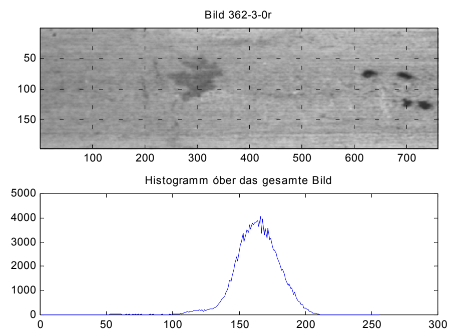


**Figure 2:** Top: Image of typical defects of different contrast acquired in reflecting light, grey level resolution 8 bit. One can see a maple leaf shaped flaw of weak contrast at the left and dark spots on the right (pickling flaws). Bottom: Distribution of grey levels. Superposed to the big gaussian distribution of the defect free surface is the small distribution of the low-contrast defect (grey level values 100 to 130) and some counts representing the dark spots on the right side at intensitiy values from 50 to 80.

The $k$-th statistical moment is given by

$$\mu_k(x, B) = E(x_i - B)^k\,, \qquad (1)$$

where $B$ is a certain constant and $x$ the sample or data set. $E$ denotes the expectation value. For $k$ =1 and $B$=0 this yields the mean of the data set $x$ or the first cumulative moment with respect to 0 (the first cumulant). For higher moments it's used to refer to the mean of the set $x$ *(B = E(x))*, then one gets the *central* moments.
The 2nd central moment is the variance

$$\mathrm{var}(x) = E(x_i - E(x))^2\,, \qquad (2)$$

the 3rd central moment is the skewness

$$skew(x) = \frac{1}{\sigma^3} E(x_i - E(x))^3\,, \qquad (3)$$

and the 4th central moment denotes the

kurtosis $kurt(x) = \frac{1}{\sigma^4} E(x_i - E(x))^4$. (4)

As one can see from equation (3) and (4), the 3rd and the 4th central moments are scaled by the 3rd and 4th power of the standard deviation, which is defined as

$$\sigma = stdev(x) = \sqrt{\mathrm{var}(x)}\,. \qquad (5)$$

From the kurtosis one often derives the *excess* which is defined as

$$exc(x) = kurt(x) - 3\,. \qquad (6)$$

Since the kurtosis of a perfect gaussian normal distribution equals 3, the excess then has to be zero and therefore is a measure for the deviation of a data set from unimodal gaussian statistics.
Fig.3 shows how image data is represented by a higher order moment. The input data are the grey levels $x_i$ along a profile through an image. The profiles are perpendicular to the wire axis i.e. a profile represents one scanned line in our arrangement. It clearly shows that the higher statistical moments indicate the occurrence of defects of low contrast with the highest sensitivity in case of kurtosis and skewness. It's substantial to this analysis that the input data is restricted to object surface and all uniformly dark background beside the object is clipped. Otherwise the background data will vastly weaken the contrast of the higher order moments signal. In practise, different wire widths and residual movements of the wire perpendicular to the axis caused by elastic oscillations and bending would require dynamical clipping. This is not easily implemented in a high-speed process. Its is shown later, how the dynamical clipping can be circumvented. A further enhancement of the sensitivity can be achieved by computing the one sided moments - regarding the fact, that the grey levels of all typical defects lie below the mean, so the 'bright side' of the histogram is ignored since it doesn't contain relevant information.
The kurtosis is a measure for the deviation of a distribution from the gaussian statistics (where the value is 3). If the distribution is combined from two or three sub-distributions with different mean, in our case the defect free surface and the darker values of a defect, the total distribution is bimodal or multimodal and the kurtosis value differs significantly from 3. An even more distinct behavior of the kurtosis one gets by smoothing either the grey levels or the histogram. Used in this form, the computation of the kurtosis provides a precise indication of defects along one axis, which is parallel to the movement. The defect position is well defined in this coordinate which suffices in principle in the case of the approximately one- dimensional geometry of the wire. The input data has to be processed line by line.

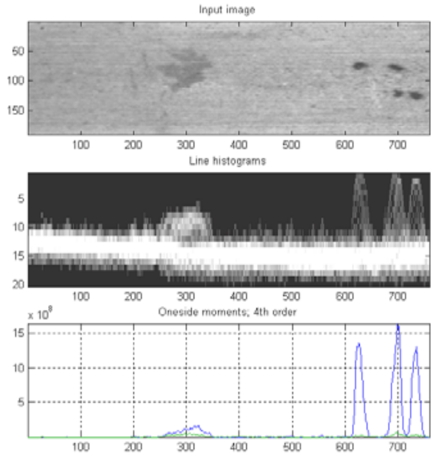

**Figure 3:** Input data sets gathered along vertical lines. Enhanced computation - one side kurtosis, background clipped. The signal of the defect free surface is practically zero for its statistics is nearly perfect gaussian. Low and high contrast defect signals have very different but clear amplitudes.

# 4 Optimization of the Kurtosis Algorithm

Computing the fourth statistical moment needs to

- reduce the mean from the input data,
- raise the mean free values to the fourth power and
- sum over the sample set.
- That then has to be divided by the square of the variance (equation (4)).

Taking into account the specific programming features for the on board DSP' s and the demand of real time processing, some adaptions are undertaken.

## 4.1 Reducing the Mean by Differential Filtering

The Reduction of the mean, if realized in sliding window technique, is familiar to a broader class of limited linear digital differential filters, like gradient-, edge enhancing or sharpening filters [3]. In some cases, the filter can be asymmetric and implies phase shifting. To obtain mean free results, the sum over the filter coefficients has to be zero. To achieve this and simultaneously reduce the noise *and* enforce gradients in a certain direction a combination of mean, differential and prediction filter was chosen. The result is computed out of the image data inside a shifting window (with dimension 1 x 8 for example - Fig.4), orientated parallel to the wire axis (equal direction of movement). Since the window moves parallel to the wire axis, gradients in this direction are enforced. In the result also the boundary between object and background vanishes, so dynamical clipping can be avoided. The filtering is implemented by means of a convolution routine.
The main point to the further processing is that from now on we process noise reduced *gradient data,* which in our case is implicitly mean free (Fig.8 - mean free image)

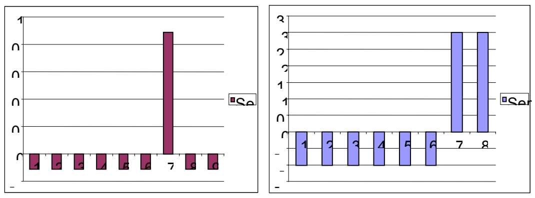

**Figure 4:** Left: One dimensional differential filter which subtracts the mean of a data set with nine elements from the $7^{th}$ element - mathematically: $x_{7,meanfree} = x_7 - \frac{1}{9}\sum_{i=1}^{9} x_i$ .

Right: Filter similar to that we used. Both deliver mean free results and cause phase shifting by asymmetry. Both accentuate high frequency content of the image.

## 4.2 Computing the Local Kurtosis

To get the kurtosis the next steps will be calculation of the fourth power of the mean free values and sum them up over a certain interval, scaled by the variance. The calculation of the fourth power can now be implemented by a simple look up table (Fig. 5 - LUT), which is a considerably fast operation.
Finally one has to sum up and scale by the variance. Comparing the summation over

different shaped areas or linear intervals on defect free surface one learns, that summing over small rectangles rather than over a line profile has two advantages:

a) If sectioned by a single line small defects generally will contribute with only few pixels in the input data set. Due to this the kurtosis signal will be relatively weak. A rectangular window (with the same number of pixels as in a line) can pick up the same defect far more extensively, so its contribution to the input is high which leads to an amplified kurtosis signal.
b) If computing the kurtosis over rectangular windows, not only one, but both defect coordinates are defined with a resolution proportional to the window size, which has sufficient accuracy.

The scaling with the variance weakens the contrast of the signal. So we skipped it. In that case the difference of 3 between kurtosis and excess becomes marginal. Further considerations also show, that one can skip the last summation, which in fact is a smoothing with a two-dimensional rectangular mean filter, this sometimes smooths out smaller defect signatures. Skipping this smoothing increases the contrast and saves processing time simultaneously. Can that all still be called "kurtosis computation"? In a broader sense - yes, but there is at least one important difference:

- In the traditional way of computing the kurtosis, *one* reduction value - the mean of the input set - is applied to this set.
  In our case the reduction of the mean is decoupled from raising to the fourth power and summation. The reduction is realized as a separate convolution, so for each point a different reduction value is applied. This enables us to give the filter additional properties, like noise reduction and prediction sensitivity, too.

This, in principle, is the stepwise implementation of a non-linear filter, outgoing from higher statistical moments, which is very sensitive to non-gaussian distributions. In processing in a last step a thresholding is performed, which skips signals below a certain amplitude. The remaining events serve as defect indicators (Fig.5 - Tresholding).

# 5 Test on Real Data

Several tests on samples in the laboratory and with material in the production line of the industrial partner yielded that continuous 100% - examination is achieved. This was enforced not only by on board DSP 's, but also by realizing a double-buffering and multi-threading programming technique. The sensitivity of $1/10^{th}$ millimeter defect size turned out to be too high for the specific material (not for the detection system!) In other words: The defects detected were sometimes so small, so a secondary 'defect area' criterion was introduced to automatically sort out very small defects (the same can be achieved by decreasing the line scan rate or the pixel-per-line number, which can be controlled through the digitizer). Since there is driven an eddy-current defect detection appliance in the same line, a first comparison between both methods was possible. It showed that the performance of the image processing system is superior or at least comparable to that of the eddy current system installed. As expected, shallow surface defects are better detected by the optical system. Very thin, but deep cracks have a better signature in the eddy current system, but are detected by both systems. The error free operation of high sensitive opto-electronic components under industrial conditions needs a lot of careful preparation especially with respect to shelter against electrical and electronical noise, which can reach high levels in an industrial environment.

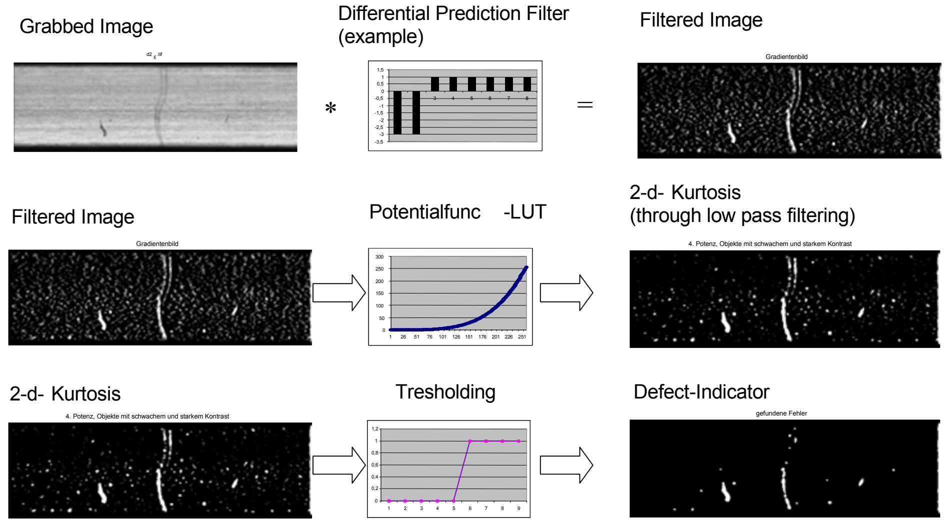


**Figure 5**: Processing steps.

# 6 Summary and Outlook

It is shown that the implementation of statistical analysis in a high-speed process can be undertaken in an efficient way. The analysis of higher order moments revealed potentials for increasing speed, resolution and sensitivity. The modification and generalization of the original kurtosis concept gives a different insight into the nature of higher statistical moments and in 'what they 're doing' to data. First attempts to express this stepwise implementation as a linear filter are presently going on and show the complexity of this concept. Further attention is paid to statistic and signal theoretical meaning and relations of this approach. The development of a defect detection appliance, which triggered this research, led to an operative system, which is adaptable to a broad field of materials, too.

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