Measurement of randomness in fiber distribution in paper using computer vision

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ABSTRACT *An automatic system for data acquisition and analysis has been developed for measuring the randomness of fiber distribution. The method is based on measuring the entropy of the image of the paper as gathered by a conventional computer vision system. The system measures both overall and local fiber randomness*

KEYWORDS
Analysis
Anisotropy
Fibers
Image analysis

The properties of paper depend on the degree and type of fiber orientation, among other factors. The exact measurement of the degree of fiber orientation has been dealt with either by the measurement of strength anisotropy or by the use of laser diffraction techniques (1-3).

It is arguable that the method of measuring strength anisotropy bears a straightforward relationship to the spatial distribution of fibers. Experiments to determine this relationship are difficult to perform, however, and the method is not likely to be suitable for an on-line measurement system.

The laser diffraction method, which is meant mainly for laboratory work in the quality control department, could conceivably be used for on-line monitoring of a localized, limited area of the paper. Incorporating such a device in a paper machine control system has its drawbacks, however, mainly stemming from the limited average lifetime of a laser.

To have an on-line system to measure fiber randomness, a method is needed that directly measures fiber randomness as the paper machine is running, using equipment with a long life cycle. Our work is aimed at developing such an automated system for acquiring and analyzing data. Our method of measuring the randomness of fibers in paper is based on the concept of entropy, in which the orientation of fibers is directly linked with the state of order.

This method performs a direct measurement of randomness through computing the entropy of the image (4) of paper as gathered by a simple, common, computer vision system. The equipment does not contact the paper and measures the whole field of view. Both the hardware and software components are long lasting.

To illustrate the use of the concept of entropy in measuring the randomness of fiber distribution, we report here the results obtained for the entropy of a kraft paper, which has a high degree of randomness. We also report the results for a printing paper, which presents a much more ordered distribution of fibers.

Entropy as applied to paper - a brief history

Thermodynamic entropy

At the peak of the industrial revolution, Rudolf Clausius discovered a new quantity and invented a new word. The name for this quantity was the result of joining up "en" from the word "energy" with the Greek word "trope," which means "evolution." This new word, "entropy," was to signify a quantity of energy that is not accessible in any system undergoing a physical transformation. Any physical system left to itself would show a tendency for an increase in its inaccessible energy. In other words, its thermodynamic entropy will grow. Of course, this cannot happen when work is being performed 9n the system.

To produce a microscopic explanation for this new quantity, Ludwig Boltzmann in 1869 showed the existence of a direct relationship between

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entropy and the distribution function of the energy of the atoms of the system. He also demonstrated that entropy was a measure of that distribution.

He proved that if the distribution function of the energy levels ε of the constituents of a system is *f*(ε), then the entropy of the system is given by:

$$S= \int f(\varepsilon) \log f(\varepsilon) d\varepsilon \qquad (1)$$

The more homogeneous the distribution function, the greater is its degree of disorder, and the higher is its entropy. This entropy is the thermodynamic entropy. The entropy relevant to our discussion here is not the thermodynamic entropy.

The entropy of a source of information: the vision entropy

Boltzmann also showed that entropy is an intrinsic property of a system, as is its mass, electrical, or geometrical properties. Its entropy is a measure of its intrinsic order. He also pointed out how it could be measured.

Any existing system exchanges mass, energy, and/or information with its environment. It is within this exchange of information that the distribution functions are to be found.

In 1.949, Shannon (5-6), unraveled the way to penetrate the whole keyboard of messages which any physical system is emitting into its environment. Shannon found that if a message x has a probability p(x) of being received, its content of information to the receiver is given by:

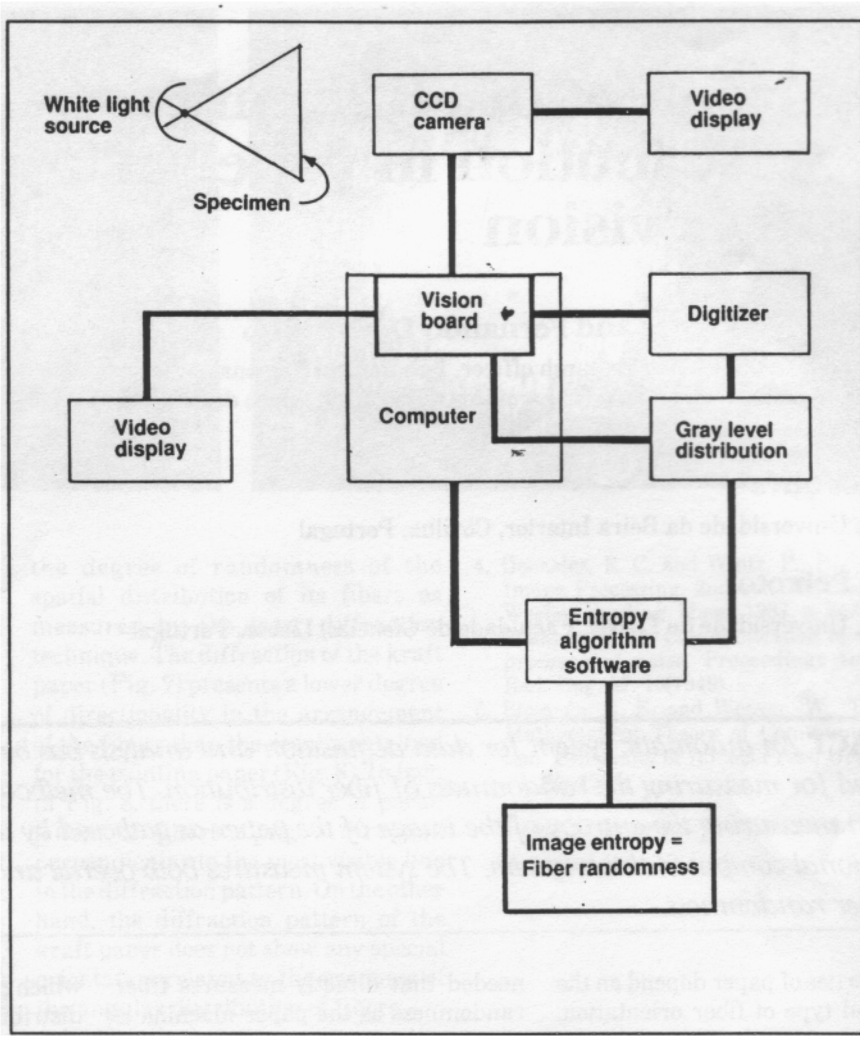
$$\ln [1/p(x)] = - \ln p(x)$$

If *n(x)* of such messages are received, the resulting content of information is *n(x)* x In p(x). If enough time is allowed for all the different messages to be received, the content of information of the distribution function p(x) of the messages is

$$S = - p(x) \ln [p(x)].dx \qquad (2)$$

This is a key result. The similarity between Eqs. 1 and 2 is striking. He called the result of Eq. 2 the entropy of the source of information. It proves that the degree of order of any system, a fundamental quantity, can be measured by analyzing the distribution function of the messages it sends. These messages come in all forms, from sound waves to electromagnetic radiation, or light.

1. Configuration for the measurement of fiber randomness



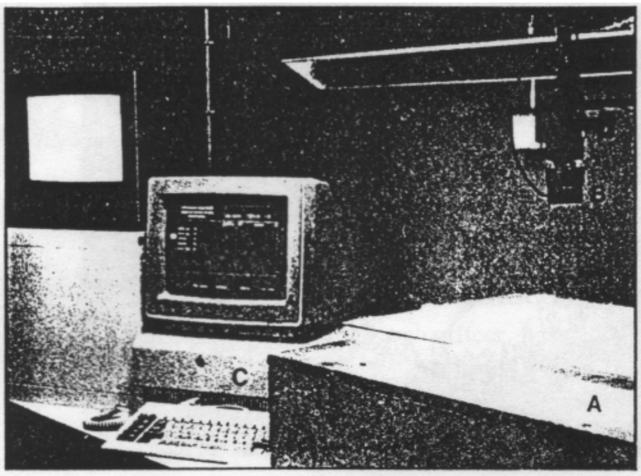
The question is, then, to choose the most adequate means to be able to compute the degree of order of a particular system by computing the content of its messages using Eq. 2.

Vision entropy

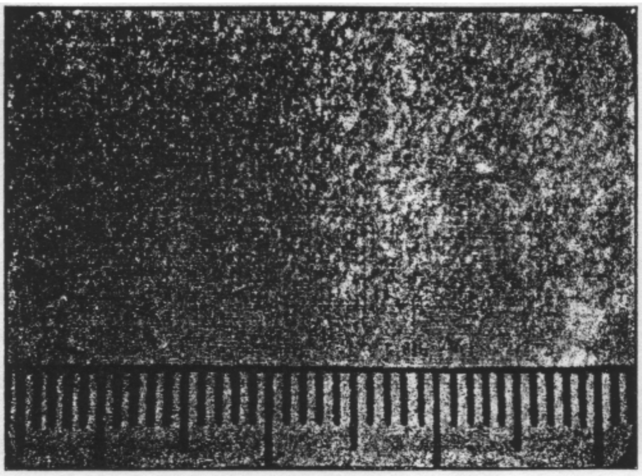
The entropy of a source of information is inferred from the messages sent by the systems. In the case of a paper product, most messages are carried by light. It is these messages that create its visual aspect, its image. Light is the privileged vehicle of information, and this type of message can be treated with Shannon's formalism.

In these conditions, measuring the randomness of fiber distribution in paper is reduced to the problem of calculating the entropy of its image. As indicated earlier, this entropic measure of a paper is as much an intrinsic property as is any other physical or chemical macroscopic property. Only this entropy is the measure of the degree of randomness of the spatial distribution of fibers in paper.

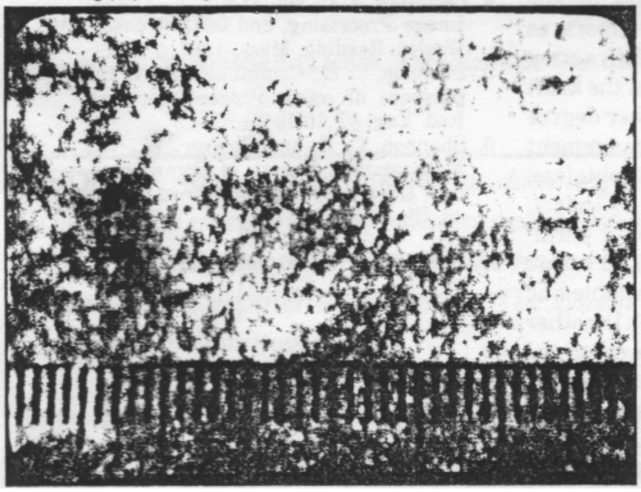
This concept can be used to great advantage in the study of the randomness of fibers in paper materials. It can also be used in measuring the performance of a process such as forming because entropy is a measure of the spatial regularity of the distribution of fibers. The higher the entropy, the more disordered is the distribution. The entropic measures of papers both finished or going through the manufacturing process can provide the criteria for quality. The concept can also allow us to make comparisons between methods and processes in industry regarding their ability to produce the right product, because quality will be related to the degree of randomness.



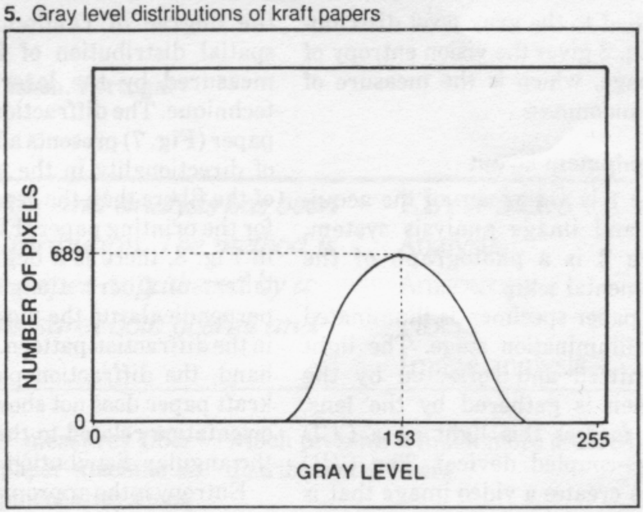
2. Setup of the experimental showing (A) the illumination stage, (B) the lens, and (C) the computer



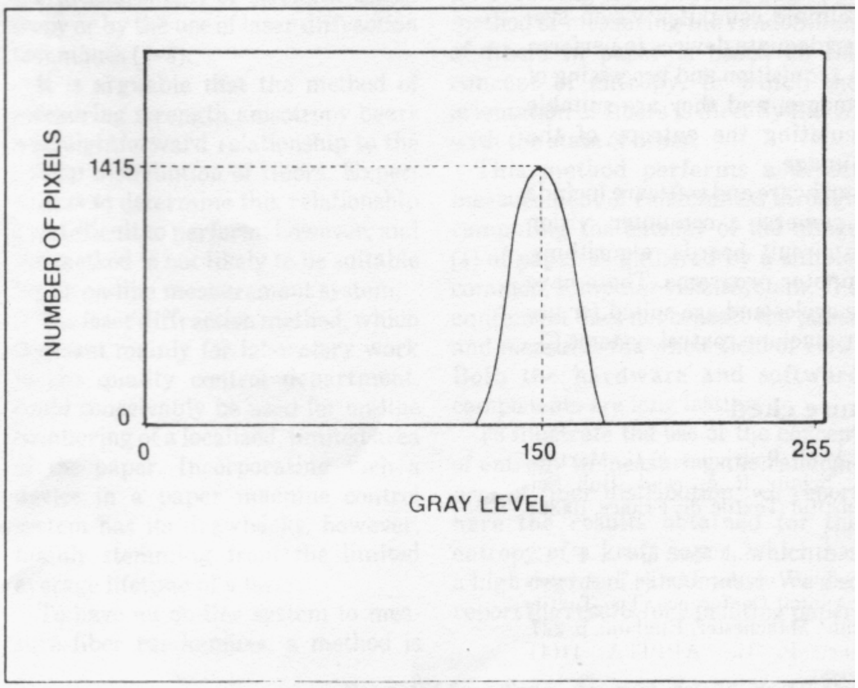
3. Kraft paper image (1 tick spacing = 1 mm)



4. Printing paper image (1 tick of spacing = 1 mm)



5. Gray level distributions of kraft papers



6. Gray level distributions of printing papers

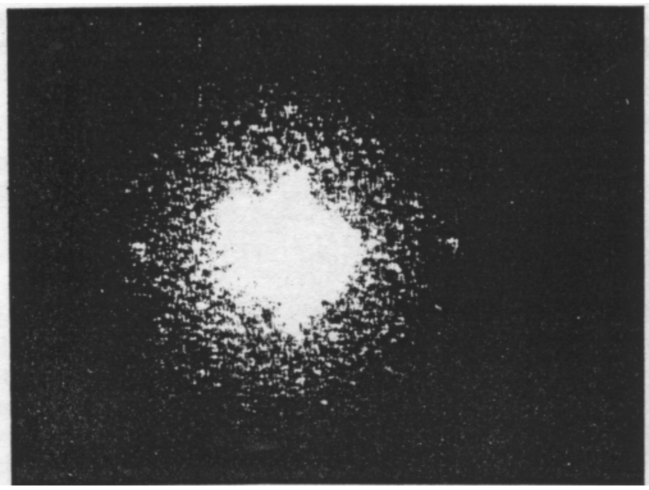
Method of measurement of fiber randomness

The theory

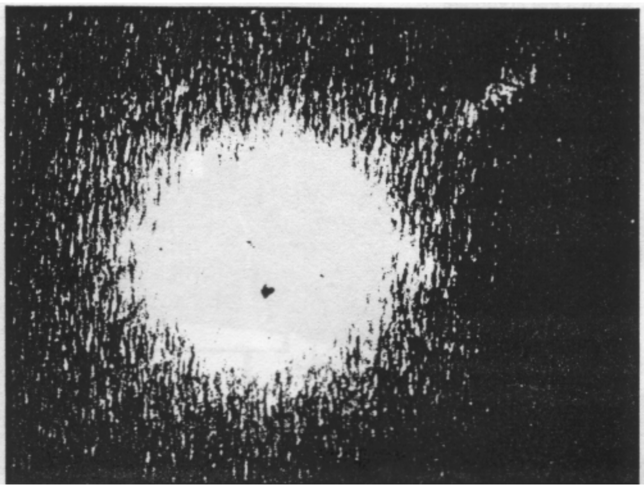
An optical system gathers the light transmitted or reflected by the paper and produces its image. The method is based on the calculation of the vision entropy of this image.

Computing the content of information or entropy of an image by any computer is a very fast affair An image is composed of finite areas that constitute the picture's elements, and these areas are known as "pixels." Each of these pixels has a certain illumination. This illumination is the elementary message, x. By counting the number of pixels that have the same level of illumination and dividing this number by the total number of pixels in the image, the probability p(x) of the level of illumination x is found. This probability is called the “gray level distribution”.

7. Laser diffraction pattern of the kraft paper shown in Fig.



8. Laser diffraction pattern of the printing paper shown in Fig.



Applied to the gray level distribution, Eq. 2 gives the vision entropy of the image, which is the measure of fiber randomness.

The equipment layout

Figure 1 is a diagram of the acquisition and image analysis system. **Figure 2** is a photograph of the experimental setup.

The paper specimen is illuminated on an illumination stage. The light transmitted and reflected by the specimen is gathered by the lens, which focuses this light on a CCD (charge-coupled device). The CCD camera creates a video image that is digitized in the computer.

The gray level distribution function of this image is computed, and the image's entropy is readily calculated using the Shannon measure, as given in Eq. 2.

To illustrate the method, we report the data for the kraft paper shown in Fig. 3 and the printing paper shown in Fig. 4. Their gray level distribution functions are shown in Figs. 5 and 6.

The entropic measure is 2.649 for the kraft paper and 2.243 for the printing paper. The standard deviations for an ensemble of 11 measurements is ± 0.09 for the kraft paper entropy and ± 0.07 for the printing paper.

Conclusions

The entropy measurements performed for kraft paper and printing palter show that there is a good correlation between the entropic measurement of a paper's image and the degree of randomness of the spatial distribution of its fibers as measured by the laser diffraction technique. The diffraction of the kraft paper (Fig. 7) presents a lower degree of directionality in the arrangement of the fibers than the results obtained for the printing paper (Fig. 8). In fact, in Fig. 8, there is a degree of parallelism of fibers along a direction perpendicular to the most visible line in the diffraction pattern. On the other hand, the diffraction pattern of the kraft paper does not show any special orientation related to the evenness of the angular distribution of fibers.

Entropy is the appropriate quantity to measure when the degree of fiber randomness in a paper or in paper formation must be assessed or monitored. Simple computer vision systems are adequate devices to perform the data acquisition and processing of paper images, and they are suitable for calculating the entropy of the paper's image.

The hardware and software include a CCD camera, a computer, vision analysis circuit boards, algorithms, and computer programs. These have long life cycles and are suited for use in paper machine control systems.

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