Latest Trends in On-line Paper Web Inspection with Imaging Capabilities

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INTRODUCTION

On-line inspection of production is a standard practice in most paper mills in the world. In India how ever, very few mills have adopted the on-line inspection of paper. It is the objective of this paper to make a case for the adoption of this global trend by the Indian paper industry as well. On-line defect analysis is the only reliable way to find all random paper surface defects like holes, spots and streaks. In addition to defect detection, the purpose of a web inspection system is to classify the defects in such a way that it helps the papermaker to trace the defect causes for their removal and to ensure that the quality of the products meets the customer requirements. The requirements mostly deal with the suitability of a product for its end use. In the worst case the defects may make the product functionally deficient or even unusable. Critical defects are also those that cause production disturbances, e.g. sheet breaks, either during the converting or at the end user production.

Automatic inspection systems for paper webs have been available for several decades. These conventional systems have utilized various technologies for detection. Their detection sensitivity was in many cases sufficient, but a shortcoming was that they were able to classify the defects only according to the size and a few gray levels, e.g. into holes, dark spots and light spots. In many systems no other information was given to the user. The most accurate information provided was the real defect shape with a few gray levels. Most of the paper defects are surface flaws, which can be detected by a human eye. Therefore, it is not a surprise that the latest inspection systems rely on optical methods as well. Recently, a new capability , the real-time imaging, has become possible adding a new dimension to this branch of quality control. These modern systems use CCD sensors to produce high-resolution photographs of the web and the defects. Paper web imaging enables the use of a large variety of modern image analysis techniques for defect analysis and classification.

IMPORTANCE OF PAPER WEB INSPECTION

CONSEQUENCES OF DEFECTS

The number of different paper grades produced on several thousands of paper machines all over the world is very large. In addition to conventional printing and writing grades, these machines produce a wide variety of different speciality papers. The requirements of paper users are rising all time, and as a result, practically all the new paper machines, and majority of the older machines, have been equipped with web inspection systems.

The main purpose of a web inspection system is to find all paper surface imperfections that are harmful to the end user or that may disturb production of converting processes. There are many types of paper surface flaws. In general, large defects are more critical than small ones, but paper users may also be concerned about defects whose diameter is only tenths of a millimeter.

First, the papermaker wants to produce paper that meets the end user's requirements. Bad quality causes problems to the end users, and they are not willing to accept out-off-quality lots. In the worst case, they may cancel the order and turn to another supplier. The surface defects on many paper grades are imperfections that degrade the esthetic quality of the final product either directly, or indirectly, e.g. by impairing the capability of printing color to adhere on it. White food wrapping paper is not allowed to contain even small dark spots due to hygienic issues. Defects in some special papers may even totally spoil products made of it (for example holes in products that should be tight,

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e.g. cigarettes, insulation materials, or wood packaging boards, etc.) Weak areas in the web can also lead to sheet breaks in converting plant or in printing house.

Second, when producing a continuous sheet at a very high speed, defects may create problems at the paper mill itself. Most harmful are those defects that cause sheet breaks. They may occur at the paper machine itself or at a later production stage. For example, large holes can cause the sheet to break under a coater blade resulting in lost production time that may be considerable, especially if the coater has to be washed as well. Similarly, defects at a winder are risky because they may cause breaks at the slitter.

REMOVING THE CAUSES

The paper manufacturer wants to make sure that the process runs smoothly and the product quality meets the customer rquirements. Therefore he needs to know, not only the emergence of defects and their severity, but also information about them that helps him to recognize the cause and to locate the place of origin.

Without a web inspection system, paper defect identification and root cause tracing can easily take several hours. To evaluate possible problems that the defects may cause during converting, the severity of defects should be identified. In most cases, defects of interest are checked visually at the winder or re-reeler before corrective action planning can begin for elimination of the source of the problem. Therefore real-time indication of defects is needed for colour marking and unwinding the defects. The same feature is necessary also for controlling calender pressure or coating to prevent breaks.

When defects are occurring frequently, a common practice is to bring defect samples to the mill laboratory. On the basis of chemical and microscopic sample analyses the best assessment or classification can be done. Unfortunately this may take hours, or even more if this kind investigations are not standard practices at the paper mill. During this delay the problem may repeat causing even more downgraded production until the problem is solved.

For defects, which originate from a specific machine part the traditional methods of a web inspection systems provide much assistance. Especially repeating defect analysis is an efficient tool. For less regular defects the profile displays (CD location) give hints about the cause. However, for random defects other means are needed. The possiblity to check visually at the operator station screen the defect appearance immediately after its detection. speeds up the severity assessment and root cause tracing. Also, automatic classification of defects according to severity and origin gives the paper maker more precise information

ARCHITECTURE OF A MODERN WEB INSPECTION SYSTEM

GENERAL STRUCTURE

A typical paper web inspection system consists of a sensor beam, a light source beam, defect information processsing electronics, and an operator station. The task of the light source beam is to provide strong and even illumination on that location of paper that is inspected. The sensors detect variations in the intensity of the light passing through the paper. Nowadays, almost exclusively, CCD-cameras are used as the sensors. A camera beam contains often tens of cameras to cover the whole paper width and to meet a specilied detection resolution. The system shown in the Fig. 1. Utilizes transmitting illumination, i.e. the light source beam and the sensor beam are located on opposite sides of the web. On high opacity paper grades the measurement has to be made by reflection, and accordingly, two beam sets are needed if both sides of the sheet has to be inspected. The systems often contain other additional devices, such as a tachometer, alarm devices, and colormarkers.

LIGHT SOURCE

There are several important requirements for a light source beam. First, it has to deliver strong illumination on the paper. This is because the paper moves fast and, therefore, short exposure times have to be used for high resolutions. Second, the intensity of illumination should stay constant regardless of varying factors like changing paper grade (opacity), lamp aging, or build-up of dirt on the beam glasses. Third, the light has to be flicker-free for uniform exposures, Fourth, light source has to be designed in such a way that the paper illumination is even all the way across the web to ensure even sensitivity of detection. Fifth, the type of the lamps has to be selected to match the specific needs of different paper grades.

Wide spectrum tungsten lamps with tubular structure provide good results. They are powerful, and their light spectrum matches well with the sensor

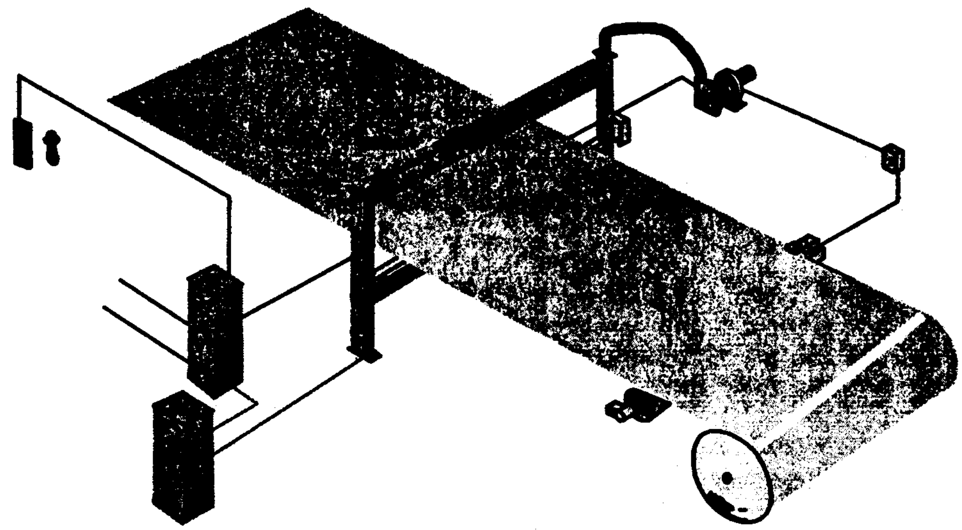

Figure 1. Web inspection frame with electronic cabinets and peripheral devices

sensitivity curve. With the help of a high quality direct current power supply, the lamp intensity can be controlled automatically according to the needs, (for example, to compensate for dirt buildup and grade changes) and the light is also flicker-free. The lamp shape (tubular) makes it easy to design a beam construction that provides strong and even illumination on paper. Wide spectrum of tungsten lamps makes them suitable to the most paper grades and defects.

CAMERAS

The cameras used in web inspection systems are either standard analog cameras or more advanced digital cameras. With the analog cameras, the video signal has first to be transferred to an off-machine electronics device for processing. For the transfer, conventional cables, which are often susceptible to electromagnetic interference, has to be used. Instead, the digital cameras have the capability to make the A/D conversion and various signal processing. Since the output of these cameras is digital information, they can use optical fiber link for the communication with the operator station, Optical fiber is completely insensitive to ambient electromagnetic interference, which ensures the data integrity during the transmission.

The sensor in the camera is a solid state device comprising of an array of light sensitive CCD (charge coupled device) cells which are called pixels (picture elements). There are two main types of arrays . They are either linear, consisting of a row of cells, or of a matrix type, where the cells form a two dimensional rectangle. A line scan camera using a linear sensor is a natural solution for web inspection because the second dimension (machine direction) is achieved with the help of web movement. Their benefits, when comparing to matrix cameras, are that line scan cameras have been designed for demanding industrial applications with high quality requirements what comes to sensitivity, signal/noise ratio, and pixel to pixel evenness. Line scan cameras are also available with a wide variety of pixel densities 512 or 1024 pixel elements are suitable for detection of holes and spots on fast machines. 2048 and 4096 pixel elements are especially needed for detection of narrow streaks. The line cameras also simplifies the design of the light source, since it is easier to realize a strong and even illumination on a narrower surface area.

Wide variety of general-purpose off-the-shelf cameras are available, either analog or simple digital devices. A system can be built using these cameras, common frame grabber boards, and personal computers. However, the computing power needed is so high that each camera requires its own computer. This adds the complexity of hardware, especially if camera density has to be high, e.g. for detection of the smallest defects.

The complexity of the real-time detection problem is easy to understand when discovering that

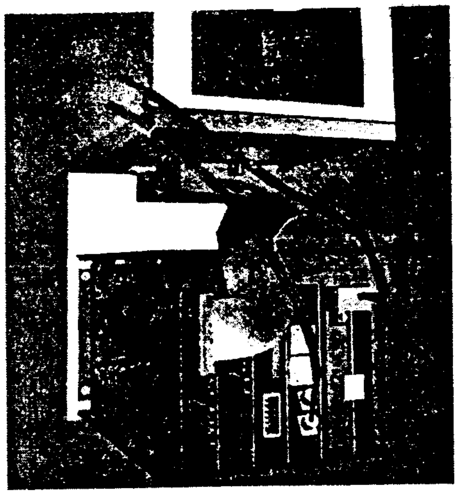

Figure 2. Modular single sensor camera

on a modern paper machine 300 square meters of paper has to be inspected each second. The task is divided between several cameras depending on the required CD resolution. A typical camera scans 20 million pixels in a second. This means digitized information flow of at least 20 MB/s per camera. It is obvious that each camera needs its own data processor. However 20 MB/s is such a high value that even a fast PC is not fast enough if it has to perform sophisticated image analysis, e.g. for subtle defect detection, on the information in real time. This is because most calculation in a PC are done in serial mode. Also, streak detection has been such a difficult task that even special cameras have been designed for this purpose only, adding the total system complexity further.

The latest developments in digital signal processing and processor technology, however, have made it possible to combine hole, spot, subtle defect, and streak detection into one single camera architecture. The solution is a compact but powerful multifunction camera system that alleviates the above mentioned problems. In the following chapter the single sensor architecture camera is described in more detail.

SINGLE SENSOR CAMERA

The sensor described here is a proprietary digital camera (Fig.2). It consists of two main parts, which are called CCD module and signal processing unit. The CCD module contains the actual light sensitive element, a linear CCD array of 512... 4096 pixels. The image of the object (the paper surface) is created on the CCD chip with a standard lens. The CCD chip outputs an analog voltage signal, which is proportional to the amount of the electromagnetic energy it is receiving.

The signal processing unit processes the output signal of the CCD module. The unit contains several electronic boards with different tasks. The boards operate in parallel to get as high throughput as possible.

The CCD module actually outputs two video signals (odd and even), which are processed separately, and the data is combined in a programmable logic device (PLD) which are processed separately, and the data is combined in a programmable logic device (PLD) which is located on one of the boards. The DC-offset is removed with the help of the so-called dark pixel reference signal. This compensates automatically for the possible changes in the ambient temperature. A/D conversion is made by a 12 bit A/D converter.

PLD is a harware gate array, which contains tens of thousands logic gates that can be wired by software to do various tasks. The logic operations can be executed in parallel just like in any hardware logic device. This makes it possible to realize fast special algorithms utilizing parallel computation. These algorithms can run truly in parallel with each other. Although PLD operates as a fast hardware, its tasks and algorithms can easily be changed if desired by downloading a new"softwiring". This provides the flexibility that is sometimes needed and also makes the system upgrades easy. This approach is completely different to the standard solution with a PC, which can make calculations mostly in serial mode. The PLD of this camera not only classifies the defects according to minimum contrasts level and size, but it also does very computing intensive subtle defect detection. Subtle defect engine operates in parallel with the tasks that handle simple defects and streaks. Also special - processing functions can be programmed into this device (formation processing, feature extraction etc.) For example, the number of pixels exceeding formation detection levels are calculated and compared to the total number of pixels.

Also a powerful RISC processor is contained in the camera to process the data after defect detection by the PLD. Its tasks include defect shape and size extraction, skipping the defects which are smaller than selected minimum size, formation index calculation, and recognition and elimination of known repeating patterns (watermarks, etc) in the analyzed sheet.

In addition, a DSP- processor in the camera is used to process the original video data to extract

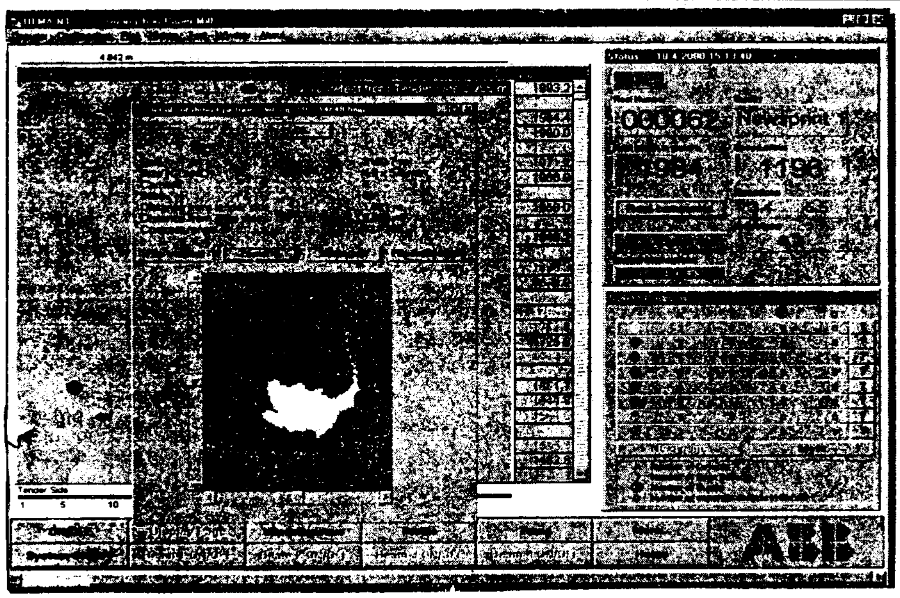

Figure 3. An operator's display

continuous flaws like streaks and scratches in the paper. The processing is done in parallel with the defect handling, which enables all the flaws to be processed in a single camera sensor. Normal integration times, which are less than 0.1ms, would be quite too short to make it possible to detect subtle continuous flaws. Therefore, separate cameras have sometimes been used for these two different purposes. In the single sensor camera, different integration times can be implemented by adjustable digital integration. The streak processing is done typically using integration of scans during 1 to 100 ms time interval.

The edges of the paper can be detected with the DSP-processor that follows the exact pixel number of the edge location. The value is used to calculate the web width from the edge location reported by both edge cameras.

A separate communication processor in the camera manages the data flow between camera and operator station. The data is received from DSP-processor and co-processors and transmitted to the operator station PC. The PC controls the displays and reporting functions and interfaces to foreign systems.

The resolution requirement in most applications is so high that multiple cameras have to be installed across the web. The number of cameras can be 1 to 8 per cross-machine meter of the web.

OPERATOR STATION

The operator station is a powerful Windows NT based PC with application specific software. The operator station combines the information coming from different cameras to form various user displays and reports. Standard local area networks are used for distributing information between operator and office stations.

The chapters above have described the sensor and system architecture to process the CCD camera pixel information into useful form for the operators. The operator station displays consists of multitude of video pages, e.g. defect maps, trends, profiles, repeating defect and formation developed for Windows NT operating system. Figure 3 shows one example page of the information presented to the paper machine operators.

DATA INTEGRATION

The basis of integrating system components, with each other and with external systems, is Ethernet local are network and TCP/IP protocol, which are commonly used in paper industry. Windows NT operating system provides the tools to realize this easily. For example multiple real time operator stations may be installed in all critical locations in the mill. Mill personnel can perform all system operations, engineering and configuration functions on the machine floor, in the

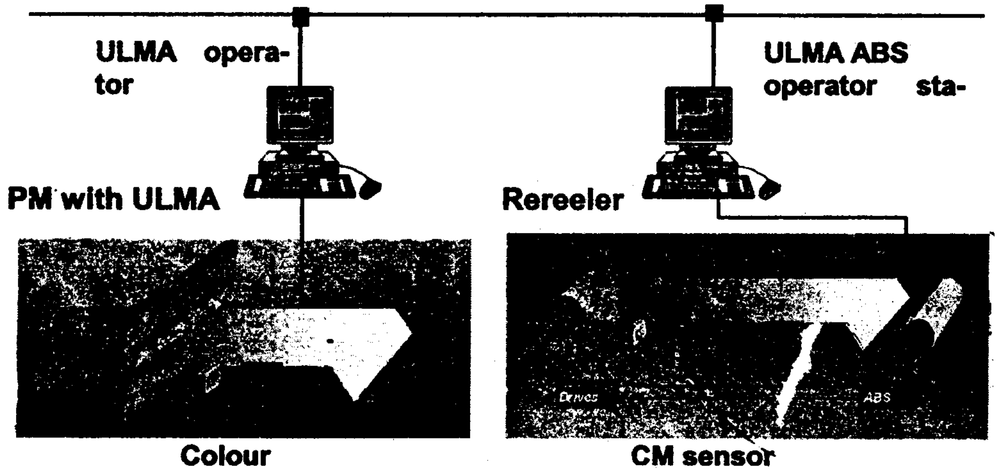

Figure 4. Automatic braking system

control room or even in office environments. The system provides also a possibility to interface with existing quality control systems.

Additionally the ULMA Web Inspection can also be integrated with the Smart Advisor paper machine diagnostic system. This integration enables the repetitive defect detection at the ULMA Web Inspection to be integrated with the information obtained from the Smart Advisor for easy root cause analysis.

ULMA UNWINDING APPLICATIONS

Detecting, classifying, reporting and locating various defects give valuable information to a papermaker. In many applications, however, also removing certain defects is necessary. An example is base paper making for coating. To avoid paper breaks at the coater severe defects such as big holes have to be removed or patched. For that purpose a colour marker is used to make visual marks on the edge of the web at the locations of those defects. In addition, reel reports give detailed information about the defect type and its location. However, finding defects manually on a re-reeler or a winder takes time and may restrict the overall production capacity. This is because the unwinding rate must be reduced to the crawl speed well in advance in order to avoid missing the defect. A tool that speeds up this task is called ABS (Automatic Braking System).

An ABS could operate only on the basis of length readings of defects received from the web inspection system and by measuring the unwinding length. However, slabbing, sheet breaks, and differences in the length counting between the paper machine and the winder result in errors in the calculated paper length. Therefore, additional colour marks, so-called calibration marks, are made at specific distances on the paper. With the help of these marks, the length counting errors can be compensated for. The colour marks are detected by the ABS with a simple optical device like a photocell. The achievable stopping accuracy is about 1 m.

The ABS system can be integrated with all types of drives. The system is operated through an ABS operator station installed at the winder or re-reeler. The operator can select easily the defects for automatic braking, either individually or by defect category. ABS calculates the optimal speed curve to the defect and controls the drive accordingly.

SUBTLE DEFECT DETECTION AND CLASSIFICATION

Web inspection systems have no major difficulties to find large defect with high contrast. Simple averaging and thresholding techniques will be adequate for detection. These methods are fast enough to detect and classify defects like holes in real time and to initiate control actions.

However, due to increasing requirements of paper users, subtler and subtler defects have to be detected. Even defects whose gray scale values are the same magnitude as the normal variation of the paper should be found. The simple but fast algorithms are not capable to detect these defects. More advanced methods are available, and they often provide excellent results in analyzing images and finding faint features when applied on images in laboratory or on images, which have been captured on the basis of some coarse defect information in the same image. Unfortunately, these methods are so computing intensive that they cannot perform the task in real time with conventional computers. For real time detection, other types of solutions have to be looked for.

A multiprocessor digital camera that meets these tough requirements was described above. A superior feature of this camera is that it can attain practically any number of complicated parallelisms inside algorithms, as also between them, at the full speed of hardware. This is in contrast to PCs and other conventional computers, which make their calculations mostly in serial mode and can not come even close to the speed of PLDs.

Wrinkles are examples of subtle defects that can be detected by this new camera. Contrast of wrinkles is often so low that the traditional methods cannot even detect them. Therefore, special algorithms are needed. They utilize the specific feature of wrinkles to enhance the signal and finally detect and classify it. The above -described camera system is the only solution available today that can perform these calculations in real time. Figure 5 shows a wrinkle and the result of the subtle defect detection algorithm.

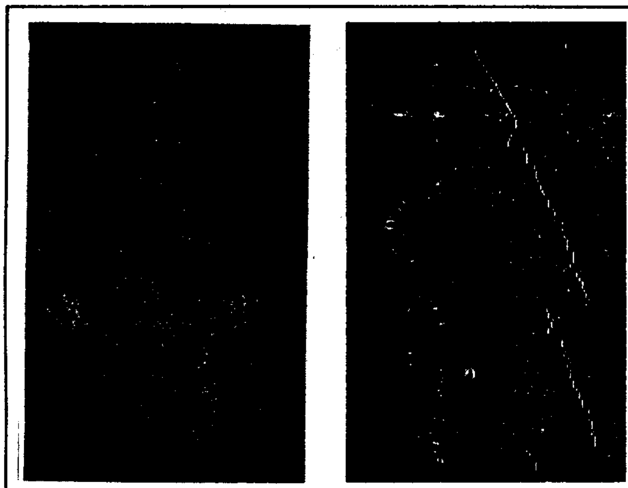

Figure 5. A wrinkle and its detection

BENEFITS OF IMAGING

DEFECT TYPES AND THEIR VISUAL APPEARANCE

In principle, all those areas of paper that deviate from the average can be regarded as defective. The number of paper surface defect types is large. Partly this is because many defect types are specific to different paper grades and paper machines. However, the defects can basically be divided into there groups: holes, light defects and dark defects. These groups arise from how the light of the illumination source interacts with the material and from the response of the sensor when compared to the signal obtained from the flawless material. Also the geometrical configuration, e.g. whether transmitting or reflecting light is used for the measurement, has effect on the result. The final classification depends of course, also on the spatial distribution of the signal.

According to their visual appearance, the defects are given different names. The traditional method to classify defects has been to use the gray scale value (or its deviation from the average value) as the main feature. In addition, these defects have been classified according to their sizes (dimensions or areas). However, it may be more useful to classify the defects on the basis of their cause and severity. The cause has to be known for its removal, and severity is needed, for example, to decide if the defect should be patched before off-line coating. In the following sections some of the most common defect types are described.

Hole (Fig. 6a) is clean if it is due to missing raw material. The cause is often a defective machine part,

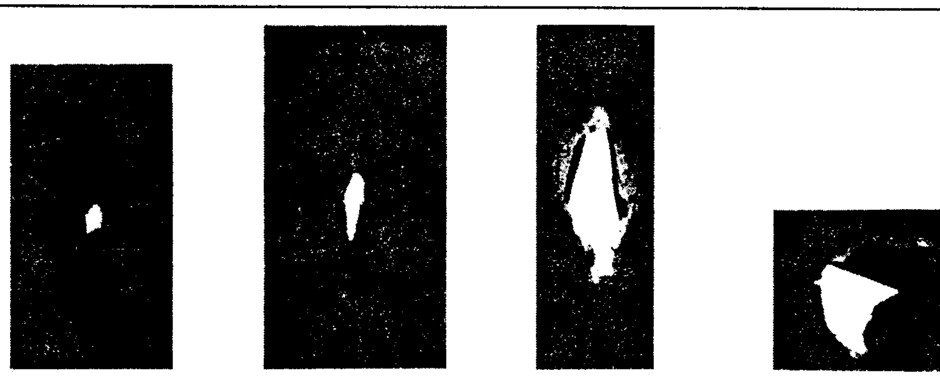

Figure 6a. Holes.

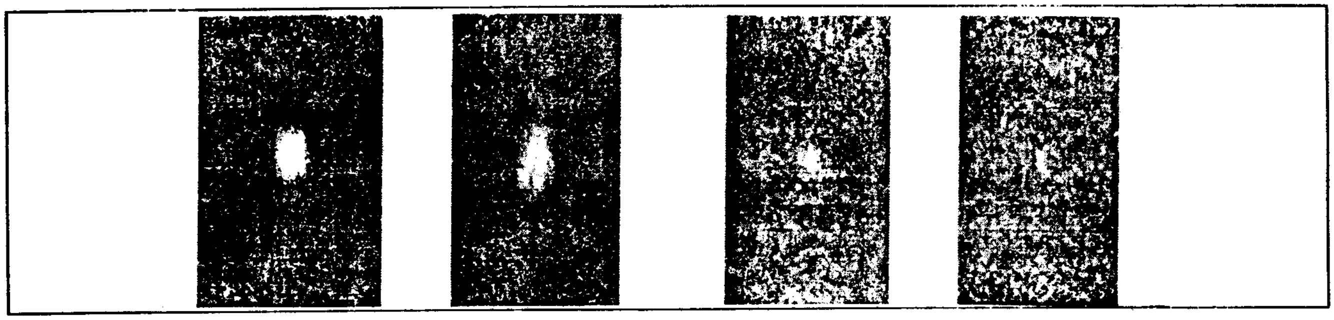

Figure 6b. Light spots

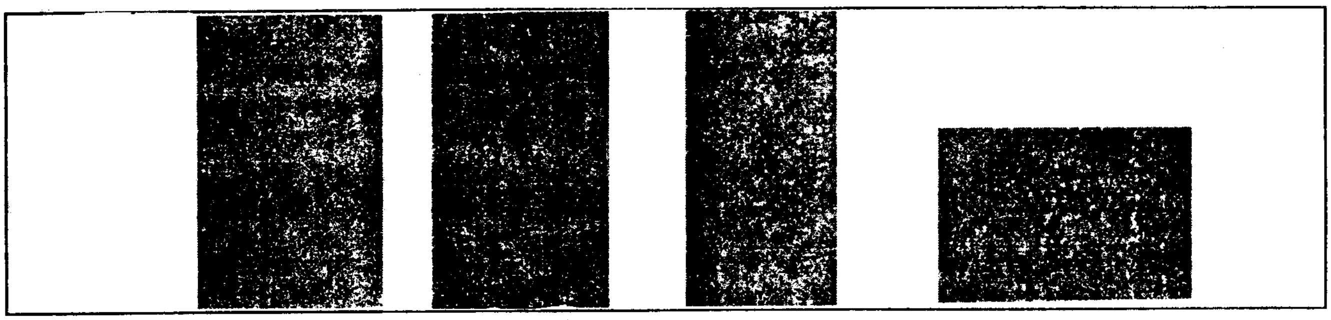

Figure 6c. Dark spots

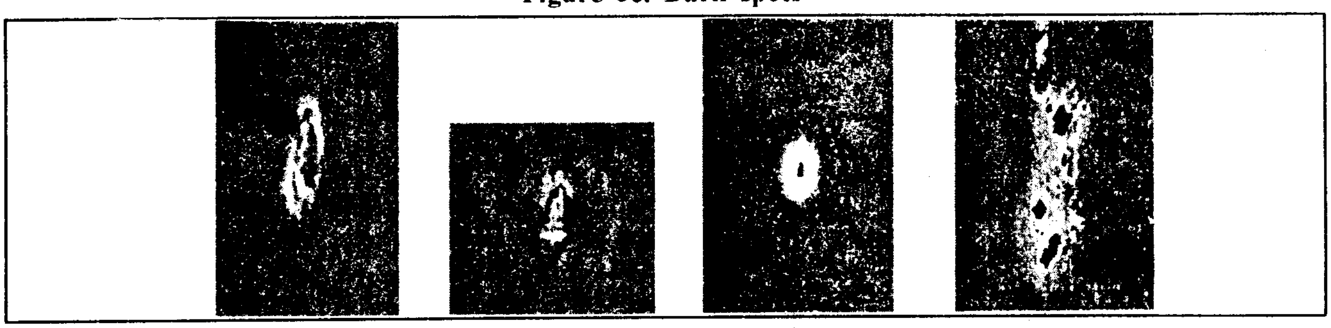

Figure 6d. Combined defects

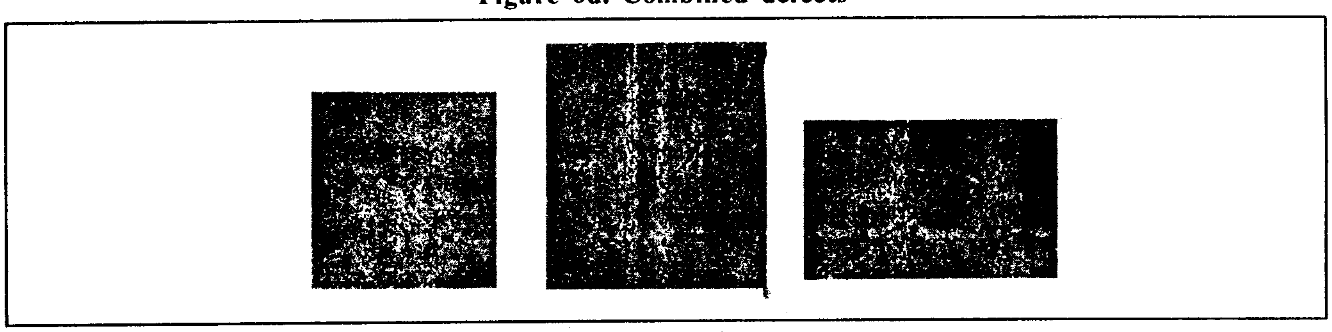

Figure 6e. Wrinkles

e.g. wire, which can be identified by repeating defect analysis. Also edge cracks and calender cuts are clean holes. Shape and location may help to separate them from other clean holes. The cause of holes with some dirt at the edges is foreign material that has been in the sheet and later fallen off. Irregular hole surrounded by dark or light areas is often called a slime hole. The cause of slime hole may be slime coming from the wet end, but also splashing size at the size press, or wet fiber clumps falling from the machine parts. These defects have very similar appearance.

Light spots (Fig. 6b) can be just small random formation errors or light spots caused by droping water or oil. The appearance of spot varies. Liquid spots have more regular shape. If dirty machine parts are causing light spots, they can be located by repeating defect analysis.

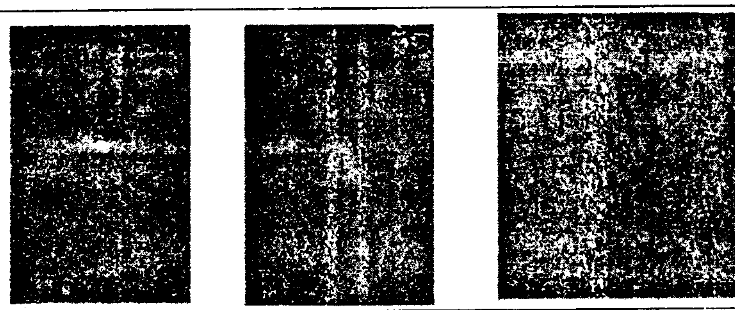

Figure 6f. Coating defects and other coating defects

Dark spots (Fig. 6c) can be any kind of dirt or scrap. These are normally random defects, and their origin is difficult to identify optically.

Combined defects (Fig. 6d) are those, which contain different amounts of hole, dark, and light areas in the same defect. Examples are so called slime holes and "fish eyes". As it is difficult to separate different slime defects, the visual differences between fish eyes and wet spots (with dirt) are often small as well.

Wrinkles (Fig. 6e) are narrow folds in the paper caused by uneven paper tension profile. The wrinkles have a typical visual appearance, but often they are quite subtle and therefore their real time detection requires a special solution

Coating streaks (Fig. 6f) are continuous defects which may be very clear and long, but they also can be short and extremely narror (e.g.0.05mm). Classifying on the basis of appearance would be easy, but the detection of subtle streaks is not an easy task.

Other coating defects (Fig. 6f) are, for e.g. skips and splashes. Skips can be very subtle and detection is the main problem. Shape can vary very much. On the other hand, coating splashes may provide a clear contrast with a specific shape. Backing roll spots have the well-known butterfly shape.

A modern web inspection system can detect and produce high quality images of various defects as shown in figures 6a. to 6f. These images are available immediately after defect detection. They are also saved in a history database for a later use. The imaging capability, as such, is useful to a paper machine operator. For example, it is especially important when the operator has to make final decisions, regarding patching at the re-reeler. The visual appearance of a defect tells the operator about the severity more than simplified results provided by the web inspection system. Also, the possibility to check the visual appearance of defects adds the operator's confidence in that the process is running and systems are functioning, as they should.

ADVANCED CLASSIFICATION

In the previous chapter the most common paper defect types were described. The main defect types can be classified also by web inspection systems. However, a more detailed classification would be useful. Image analysis with pattern recognition has attained fine results in many applications.

When running a paper inspection system, a typical observation is that the most of the defects (almost 95%) are small light and dark spots. These small defects have typically no special feature, which could reveal its origin. The result of a visual assessment can be that "something has dropped on the web", "dirt", "scrap", "liquid spill", or something similar. Only if a defect is repeating at the same interval the cause can be located by the repeating defect analysis, which tells it's origin. This is valid also for larger repeating defects. There is no need for further analysis. By cleaning or repairing the defective machine part the cause can be removed. It these defects are randomly occuring, the origin may be possibly found by a chemical or microscopic analysis in the mill laboratory.

To a certain extent the cause and origin of defects can be analyzed and classified from defect images using, for example, neural network methods. For example, slime holes have some specific features, which can be used for its automatic classification. However whether the substance is slime, size, or wet fiber clump is almost impossible to determine on the basis of image information. There is some other defect types, which have typical visual appearances. Examples of such defects would be calender cuts, liquid spots, and "butterflies",etc.

Streaks and wrinkles are other specific defect types, for whose classification special algorithms have been developed. The methods have been specially designed for these defects and their reliability is also very good.

RESULTS ACHIEVED

The ULMA Web Inspection System has been very successful in generating a payback period of less than twelve months. The ULMA Web Inspection has been acknowledged, by the users, to help them significantly in reducing the sheet breaks and speed up the identification of defects. To highlight this point let us take the case of a European fine paper (coated and uncoated)mill. The ULMA is installed at the PM#6 which has a 4.8m deckle. Some of the grades produced here have a 100% recycled content while others are based on at least 50% recycled content. The mill wanted to install a Web Inspection system to help them maintain a high uniform quality. Because the raw material is recyled, the machine is very susceptible to problems related to stickies, which attach to the wire, rolls and the felt. This leads to holes and spot on the web. With the installation of the ULMA web Inspection system these problems can be detected at an early stage and thus sheet breaks and rejects avoided. Additionally, with the repetitive defect analysis feature, the ULMA identifies the part to which the stickie is probably attached.

CONCLUSIONS

The latest developments in paper web inspection have made possible to take high-resolution images of the paper covering the whole web in real time. Simple algorithms are able to examine the huge data flow coming from cameras and to find distinct defects. The defect images are saved in computer memory and they can be used to aid the daily operations like paper machine diagnostics and patching decisions. The defect images can further be analyzed and classified by customary computers. However, the detection of subtle defects like wrinkles and streaks is more complicated and computing intensive task. An intellegent digital camera, developed by ABB, has been described in this article. This camera system has been realized with latest PLDs, DSPs and RISC-processors. The single sensor camera detects all the defect types in the same unit: the common holes and spots, streaks and subtle defects. Only this type of powerful multiprocessor system has enough processing power to locate and classify also the subtlest defects in real time. The installation of the web inspection system does not require any additional machine modifications. It is typically installed just before the pope reel and before the O-frame scanner, if it is present. The O-frame scanner is already existing in most machines that consider the installation of the Web Inspection. If the O-frame scanner is already installed, then the same can be interfaced with the Web Inspection System. About 500mm of space in the MD is required for the installation of a transmission type Web Inspection System. The reflection type of systems may require additional space. Additonally the mill must consider about 6hrs machine stoppage for the beam installation and camera tuning.

The ULMA Web Inspection has been installed in about 60 machines in the year 2000 itself. In total there over 900 ULMA Web Inspection Systems installed in the world today. The Web Inspection is a great competitive tool for the Indian papermaker to provide superior quality to their customers and to enhance the value of their product. It is an invaluable toll for the new as well as existing paper machines. This is true not only for speciality grades (like cigarette and coated grades) but also for regular grades like newsprint and writing printing, etc.