

Condition monitoring of paper machine with thermal imaging

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ABSTRACT

This technical paper describes the requirements to effectively use thermal imaging as a means of monitoring rotating machine components in a paper machine. The present efforts are focused mainly on monitoring polymer-covered rolls in paper machine calenders, but the studies will be expanded in the future to monitoring the temperature profiles of paper machine press fabrics and press belts in shoe presses. The main challenges in these areas are the high speeds of the target surfaces, obtaining adequate temperature difference resolution at relatively low surface temperatures and challenging environmental conditions. Adaptive triggering is discussed as a synchronization method for obtaining an adequate number of images from the target. Also some image processing techniques, test results and required qualities of infrared camera technology are presented.

Keywords: adaptive triggering, synchronization, continuous monitoring, rotating components of paper machine

1. INTRODUCTION

Predictive condition monitoring has a central role in the maintenance of paper machinery since the aim is to maximize the availability of these expensive manufacturing units and to avoid unexpected damage or mechanical breakdowns. Thermal cameras could be used for detecting occurrences or changes that are undetectable by other measurement methods. In fact, Metso Paper has used portable thermal cameras for many years in troubleshooting and service. So far, the systems have been based on portable cameras and slow-speed line-scan cameras. There are only few continuous, on-line monitoring and control products on the market and these are mainly in the metal industry. Is it now the right time to realize the value of these continuous monitoring techniques in the paper industry?

The papermaking process has several potential targets for the application of thermal imaging. Research has been concentrated on the polymer-covered rolls of calenders but it will be extended to the press fabrics and the press belts of shoe presses. The calender is one of the finishing parts in the paper machine process. It is comprised of from 6 to 10 polymer rolls and about the same number of heated metal rolls. Temperature differences, called as hot spots, on the surface of a calender polymer roll can damage the roll and cause a shutdown of the entire papermaking process. The cause of a hot spot is usually dirt or paper coating material that sticks to the roll surface. These foreign objects cause impacts every time they go through the nip, which is the area where two rolls are pressed together. The repeated impacts will heat the surface and, due to its low coefficient of heat expansion, the surface will expand. This increases the impact power, leading to a series of events that eventually breaks the surface of the polymer covering. The cost of roll damage is very high due because of the cost of repair or replacement of the cover and the loss of paper production. Furthermore, a breaking roll cover can raise a serious risk of injury to the people working close to the calender.

Polymer rolls may be damaged also as a consequence of line load failure or excessively high surface temperatures of the metal rolls next to it. Typically these failures do not cause hot spots but result in thermal bands around the polymer roll. Continuous thermal bands are easier to detect and do not result in remarkable vibrations. Filling of the press fabrics caused by dirt and other contaminants will unevenly wear the fabrics, thereby shortening their service life. Also, the water content in these areas differs from those that are clean, causing problems with the paper quality.

These counterproductive occurrences can be detected with infrared cameras due to the differences in temperature or water content. Temperature differences on the polymer roll cover are more time-critical. The series of events leading to calender roll damage can occur during a few minutes. In contrast, press fabric damage can occur over few hours.

After its initial creation, the temperature difference on a calender roll tends to increase by the emergent vibration caused by the heat expansion. The vibration levels are usually too low for being reliably detected by accelerometers across the entire width of a roll. With the information provided by thermal images operators can decide and carry out the most appropriate actions for ensuring trouble-free production. In a calender this often means decreasing the line load or the surface temperature or even taking a shut down for cleaning the roll surface. In the case of fabrics, washing showers can be aimed at filled areas. Using online information, the remaining service life of the fabrics can be estimated in order to plan the optimum moment for changing the fabrics.

Detecting calender hot spots is challenging since they are just 5-15 millimeters in diameter and their travelling speed can be up to 2000 m/min (33 m/s). To attain adequate spatial resolution in the machine direction, synchronization and certain camera techniques are required. The other challenge is the relatively low temperature (40-120°C, 104-284°F) which is critical to reach an adequate signal-to-noise level. The optimum spectral range for an infrared camera in these temperatures is 7,37-9,25 μ m. Moreover, the acceptable temperature difference between a harmless hot spot and its surrounding surface temperature is just 3 to 10 degrees Celsius. For these applications, thermal imaging does not require precise accuracy of the absolute temperature but a good ability to detect temperature differences. The emissivity of the polymer cover is relatively high (0,96) which eliminates reflections coming from the environment. However, the emissivity decreases as the angle between the normal of the roll surface and the optical axis of the camera increases. Because of the convex shape of the roll surface reflection needs to be eliminated by using line-scan cameras or by reading only a flat area from the detector of a matrix camera.

2. ADAPTIVE TRIGGERING

The integration time of fast infrared cameras, e.g. quantum well cameras, is generally noticeably shorter than the time between two consecutive images. In other words, these cameras give non-continuous images of fast-moving targets. But the objective is to create an image that completely covers the target surface. To create a full, continuous image, synchronization is required to fill in the blank areas between images. With synchronization, the images of the target surface will begin at the same location. This allows averaging of consecutive images. Averaging increases signal-to-noise-ratio (S/N-ratio) but decreases contrast respectively. Thus it must be used just for reaching adequate S/N-ratio.

Adaptive triggering is a synchronization method that can be used for imaging continuous and repetitive occurrences that have relatively high speed proportional to the frame rate. This is the case when we are imaging rotating paper machine components at full speed. With adaptive triggering, the particular areas of the object surface can be imaged by assigning the exact moment of each frame. The whole target surface will be imaged during a finite number of rotations. The start of each rotation of a roll or fabric is determined by a trigger sensor, described later.

Figure 1 shows how images can be focused on certain sectors of a calender roll by adaptive triggering. The image on the left shows the areas covered by two consecutive images taken in the same rotation. These areas consist of Field Of View (FOV) and stretched image due to movement of the object during camera's integration time. The image on the right shows areas covered by images taken in four sequential rotations. The arrow illustrates the blank area that reduces in every subsequent rotation until the whole surface has been imaged.

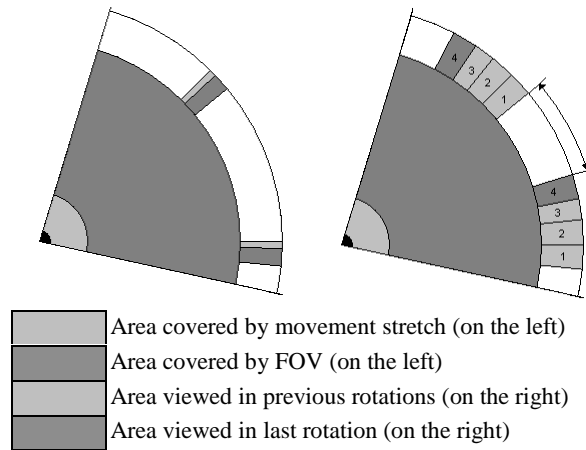


Fig. 1

Imaged area covered by Field of View and the stretch due to the movement on the left, and the accumulation of viewed area during four rotations on the right. The number of each rotation is marked in the viewed areas.

The exact area of the object surface is imaged by delaying the trigger signal and by using the delayed pulse as an external triggering signal to the camera. Hence the images can be focused on the interesting areas of a rotating object. By knowing the location of interesting or blank areas on the object surface, and its speed, the needed delay can be calculated (Equation 1). In the Equation 1 y_{blank} is the distance from the trigger to the object area, $y_{surface}$ is the length of the circle and $f_{rotation}$ is rotation frequency (Hz) of the roll.

$$t_{delay} = \frac{y_{blank}}{y_{surface} \cdot f_{rotation}} \quad (1)$$

Although adaptive triggering enables us to choose the areas we want to image there are challenges related to the existing infrared camera technology. Only a few of these cameras have an external triggering mode. That is the most critical deficiency. Moreover, most of the cameras that have the external triggering mode will read an incomplete frame at its end while they would get the trigger signal during the reading. Hence the starting moments of externally triggered frames are uncertain and they must be checked afterwards. For this we measure the time between the trigger and the vertical synchronization signals of every image. With this information and solving the y_{blank} term from the Equation 1 we are able to calculate the actual location for each frame in the entire image of the roll surface.

Figure 2 shows the imaging equipment used for adaptive triggering. The arrows show the direction of signals between the equipment. The pulse sensor (trigger) is either magnetic, inductive or light sensitive. The needed delay between the trigger signal and the image capture from a particular area of roll surface is calculated with a PC. The delay module performs timing based on the calculated delay value, and triggers the camera when the delay has elapsed since trigger signal. The level triggering of the signal is adjusted in the FIM 140 -module. Thereafter, the signal is processed by the I/O-card (PCI-6601) and by the frame grabber (PCI-1422). The manufacturer of the cards is National Instruments. The signal adapter is a terminal strip that is used for reading the vertical synchronization signal of each frame. The delay module determines the elapsed time between the vertical synchronization signal and the trigger signal. Based on this information the frame can be focused into the object image.

The external delay module is used instead of a PC because of the PC's uncertainty of triggering accuracy. The software used (LabVIEW) brings on changing triggering delay of 1-4 milliseconds. The locations of images would therefore differ from 33 to 132 mm from the wanted location. The accuracy of the external delay module is determined by its clock frequency that is noticeably shorter than the delay caused by software.

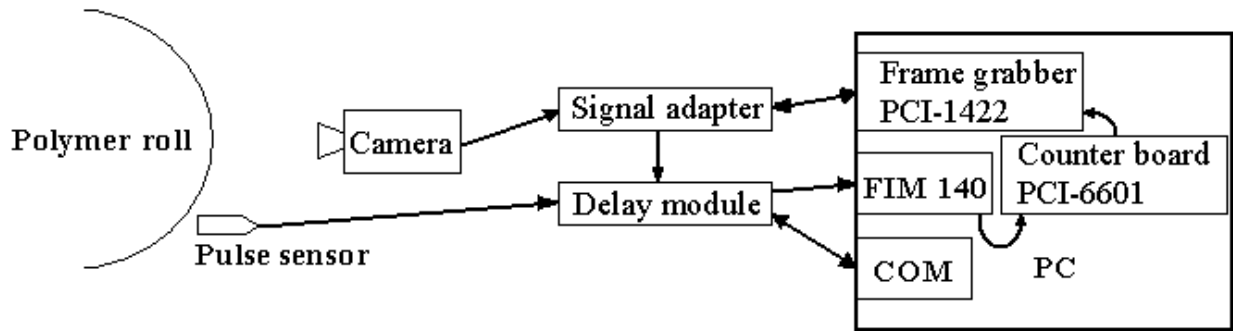


Fig. 2

Imaging equipment with adaptive triggering devices. The PC calculates delay time for every frame. Delay module triggers camera based on this value and pulse sensors signal. Then the signal adapter reads the vertical synchronization signal from the triggered frame. The delay module determines the elapsed time between trigger signal and the vertical synchronization signal of the frame. The time value is used for appointing the exact location of the frame in the image of the roll surface. Camera's triggering signal goes through FIM 140-module, PCI-6601 counter board and PCI-1422 frame grabber. PC communicates with the delay module through its COM-port.

3. IMAGE PROCESSING

Due to the fast-developing nature of polymer roll damage and because the generation of complete images of roll surfaces takes several rotations, the usable time for image processing is limited. The first object is to quickly alert the machine operators to potentially harmful situations. After gathering more experience from these occurrences some automatic alarm functions will be used. Thermal bands that continue around the roll surface can be detected from temperature profiles of the image (see Figure 3). Temperature distribution on the polymer roll surface is usually very regular. This enables the use of residual calculation as a means for detecting spot-like objects that differ from the average temperature. The calculation compares simply the temperature value of each pixel with the mean temperatures in the cross direction and machine direction. The operation is fast enough for on-line monitoring and highlights hot spots as Figure 4 demonstrates. The residual value for each pixel in the temperature image can be calculated as follows:

$$r_{x,y} = T_{x,y} - \bar{T}_{CD_y} - \bar{T}_{MD_x} + \bar{T}, \quad (2)$$

where $r_{x,y}$ is the residual value of temperature in point (x,y)

$T_{x,y}$ is original temperature value in point (x,y)

$$\bar{T}_{CD_y} = \frac{1}{N_{CD}} \sum_{j=1}^{N_{CD}} x_{x,j} \quad \text{is the mean temperature value of single line y in cross direction}$$

$$\bar{T}_{MD_x} = \frac{1}{N_{MD}} \sum_{i=1}^{N_{MD}} x_{i,y} \quad \text{is the mean temperature value of single column x in machine direction}$$

$$\bar{T} = \frac{1}{N_{CD} N_{MD}} \sum_{j=1}^{N_{CD}} \sum_{i=1}^{N_{MD}} x_{i,j} \quad \text{is the mean temperature of the complete image}$$

N_{CD} is the number of pixels (columns) in the image in cross direction

N_{MD} is the number of pixels (lines) in the image in machine direction

The mean temperature value term \bar{T} of complete image is used for returning the original intensity level that decreases due to residual calculation. This was the best way for us to compare residual images with original images. However, the term can be ignored or replaced with other suitable correction factor depending on the need of application. In addition,

averaging several consecutive images of the roll surface can be used for increasing signal-to-noise-ratio. Nevertheless, this attenuates contrast and must be used only if necessary.

4. IMAGING TESTS

The first imaging test was made for determining the possibility to detect fast moving and small-sized occurrences with existent camera technology. In the test no synchronization methods were used. The tested digital quantum well camera, SC 3000, is made by FLIR. An Inframetrics 740 camera with high-speed line scan mode and two bolometers (Inframetrics SC 1000 and Raytek MP 50) as points of comparison.

The frame rate is proportional to the height of the sub-images in the case of SC 3000 while the width of images is constant, 320 pixels. The camera always sends fifty frames (320 x 240 pixels) per second. If the actual frame rate increases, the size of sub-images must be decreased in same proportion for fitting the sub-images into the frame to be sent. The temperature range affects the integration times and thereby the highest possible frame rates. The SC 3000 has five frame rates and consequently five sizes of sub-images. The key parameters of the camera are shown in Table 1. In the test the highest temperature range was ignored due to its low signal-to-noise ratio.

Table 1.

Frame rates, integration times, Noise Equivalent Differential Temperatures and Signal-to-Noise-Ratios for the temperature ranges of the SC 3000. On the right are shown the sub-image sizes for the frame rates.

Temperature range [°C]	Frame rates [Hz]	Integration time [ms]	<i>NEDT</i> [mK]	<i>SNR</i>	Frame rate [Hz]	Size of sub-images [horizontal x vertical]
-20 ... 80	50, 150	3	20	250	50	320 x 240
10 ... 150	50, 150, 250	0,5	40	125	150	320 x 80
0 ... 500	50, 150, 250, 750	0,1	120	41	250	320 x 48
350 ... 1500	50, 150, 250, 750	0,1	-	-	750	320 x 16

The test equipment contained an industrial PC with 1 GHz processor and 512 Mb memory. The user-interface for the system was made with National Instruments' LabVIEW-software because it enables rapid software development. The frame grabber, PCI-1422, was also made by National Instruments'. At the full web speed, the image of roll surface was refreshed at 3-5 second intervals. As the web speed decreased the height of images increased leading to longer refreshing intervals.

As a first test experiment, spots made of paperboard were glued on the roll surface. They were supposed to warm up as they touched the hot metal roll. However, as the web speed and the cooling effect of airflow increased and as the contact time of the spots and the metal roll decreased, the temperature of the spots decreased so that they couldn't be seen. More applicable objects for high web speeds had to be developed. The solution was to use reflective material that wouldn't need heating by the metal roll. They reflect thermal radiation from the environment. A triangle and spots made of aluminium (5 and 10 mm in diameter) were glued on the roll surface. These spots could be seen at all web speeds but the absolute temperature difference between them and the surrounding roll surface remained undefined.

Figure 3 shows an image of the polymer roll surface and 2D- and 3D-profiles of it. The image was taken at a low 100 m/min web speed. Therefore, the paperboard spots can be seen. The image shows the cooling effect of the paper web as the temperature of the web area is lower than at the roll edges. As well, a narrow area that was warmed with a hot air blower can be seen clearly. The 3D-graph shows that the actual image size is about 320 x 9000 pixels so the thermal image shows only a part of the roll surface. The imaging distance was about 2500 millimeters.

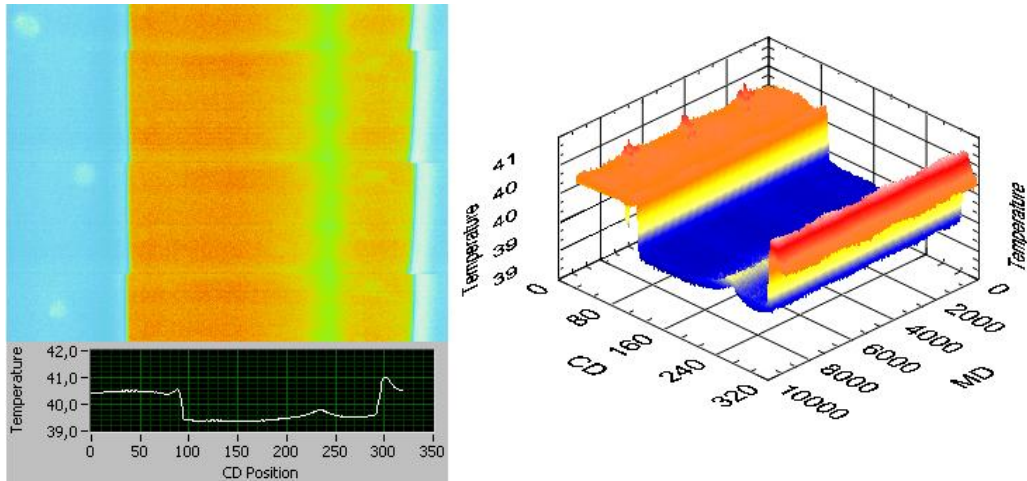


Fig. 3

Image of the roll surface and 2D- and 3D-profiles at 100 m/min web speed. The profiles show the cooling effect of the paper web. Also, paperboard spot and the narrow warmed area can be seen from the image.

Figure 4 shows three images of a roll cover imaged by the SC 3000 at the full web speed (1800 m/min). Again, the images show only parts of the whole roll image. The circled areas show the location of the aluminium spots but unfortunately the printing technique dims them. In the image on the left the integration time is 1 ms, the frame rate 50 Hz and the height of a single sub-image is 80 pixels. In the other two images the figures are 250 Hz, 0,1 ms and 48 pixels. The image on the right is the averaged residual image of four images in the middle. It shows that the temperature differences can be highlighted by residual calculation while averaging lowers noise level.

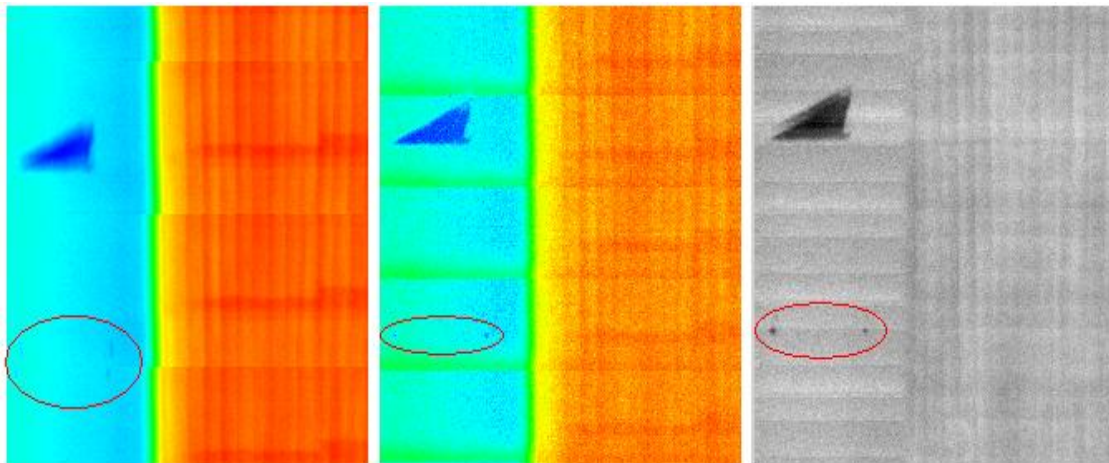


Fig. 4

Three parts of the roll surface images at 1800 m/min web speed. In the image on the left the frame rate is 150 Hz and the integration time 1 ms and in the other two images they are 250 Hz / 0,1 ms. The image on the right is the averaged residual image. Circled areas show the location of the aluminium spots.

Due to the high web speed the integration time is the key parameter for eliminating image blurring caused by object movement. The results of the tests indicate that the integration time in the application should be at most 1 ms to prevent the blurring of objects. The noise level of an imaging system defines the lowest possible integration time. In the case of SC 3000 the limit is about 0,1 ms since the signal-to-noise level was then barely 40. The SC 3000 was quite appropriate for detecting hot spots even at the highest web speeds. Its problem is that it has active cooling system and thereby needs regular maintenance.

5. REQUIREMENTS FOR CAMERAS

The environment in paper machine is very demanding for the mechanical, optical and electronic properties of any measurement device. The ambient temperature can rise up to 60-70°C (140-158°F) while the relative humidity of air is sometimes above 95 percent. The huge electric drives of paper machine rolls cause electromagnetic disruptions and heavy vibrations. Furthermore, particles and droplets billowing in the air especially in the wet end of a paper machine will soon foul the optics of cameras. These circumstances must be considered before any measurement device can be evaluated as a continuous one.

Table 2 shows some requirements for ideal camera qualities in the monitoring applications of a paper machine. The requirements are based on imaging tests and a theoretical approach to the subject. The definition of pixel frequency f_{pixel} is multiplication of frame rate f_{frame} and the number of horizontal lines in detector y_{pixel} (Equation 3). Its purpose is to ensure enough accurate image resolution in the machine direction.

$$f_{pixel} = f_{frame} \cdot y_{pixel} \tag{3}$$

Note that each of the three cases (A, B and C) have some dissimilarities. As well, the required frame rate for line scan cameras is higher than for matrix cameras. It is also worth to mention that actual monitoring application will most probably be less efficient than the ones in the Table 2. This is because the cameras that can fulfil the qualities below are usually expensive quantum well type cameras that need powerful cooling systems

Table 2.
Ideal camera qualities for the monitoring applications of paper machine.

	A (asynchronized)	B (synchronized)	C (synchronized)
FOV-angle	80°	80°	80°
Pixel frequency	13300 Hz	1330 Hz	1330 Hz
Spectral range	7-9 μm	7-9 μm	7-9 μm
Measurement range	40-120°C	40-120°C	40-120°C
Maintenance free time	9000 hours	9000 hours	9000 hours
Accuracy	±2°C tai ±2%	±2°C tai ±2%	±2°C tai ±2%
NEDT	±0,2°C	±0,2°C	±0,2°C
SNR	50	50	50
External triggering	no	yes	yes
Line scan camera			
Frame rate	13300 Hz	1330 Hz	1330 Hz
Integration time	0,075 ms	0,38 ms	0,38 ms
Detector resolution	550 x 1	550 x 1	550 x 1
Matrix camera			
Frame rate	850 Hz	100 Hz	50 Hz
Integration time	0,1 ms	0,5 ms	1 ms
Detector resolution	550 x 16	550 x 14	550 x 27

The Field-Of-View should be as large as possible for eliminating the required number of cameras. The aim is that, at most, three or four cameras would be needed for monitoring rolls up to ten meters in width. As mentioned before, the ideal detector for eliminating reflections due to convex roll surface is the line-scan detector or flat matrix detector. When monitoring machine fabrics this is not critical, so normal sized matrix cameras can be used. A possibility for accurate external triggering is a key feature when the purpose is to use adaptive triggering. Still it can be possible to use cameras that can read the detector continuously so that the integration time is about equal with the time between two consecutive images. However, the integration has to be short enough for detecting fast moving objects. Digital output is also a desirable feature to prevent disruption in signal transmission.

6. CONCLUSIONS

The test results make it clear that thermal imaging combined with adaptive triggering has great potential to continuously monitor paper machine components. In the near future it is necessary to find out which of the infrared cameras are most appropriate for these applications. We are also looking forward to see how cost efficient bolometers can perform in comparison to the quantum well cameras. Then thermal imaging will truly be able to take its place in the paper industry.

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