ONLINE DETECTION AND CATEGORISATION OF DEFECTS ALONG CARBON FIBRE PRODUCTION USING A HIGH RESOLUTION, HIGH WIDTH LINE SCAN VISION SYSTEM

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Abstract

During carbon fibre production as well as fabrication of follow up products such as preforms various defects affecting quality and performance of the finished product may occur. While numerous defects such as fuzz balls, roving twists or undulations are easy to identify, filament fractures or inhomogeneous binder distributions are challenging to detect and monitor. Typical carbon fibre filament diameters lie within the order of 5-7 µm in contrast to a production line width of 2-3 m as commonly observed in mass production, make the detection of fibre fractures difficult. Similarly, the online observation of binder distribution along a production process is a challenging issue. Thus high image resolution, a large scan width as well as a high image acquisition rate in accordance with the production speed are inevitably required for proper monitoring purposes.
Based on the above, the current study focuses on a system developed to increase scan width at very high resolution. The limiting factor for image acquisition remains the data transfer rate. In this study, the scan width is maximized through the the use of a line scan camera and a specialized optic. This optical system allows the continuous capture and the increase of the monitored area with a magnitude of three compared to current optics, with no loss in acquisition rate. The software processes the acquired camera information for image segmentation. The algorithms then scan various sets of lines in the image and highlight specific Regions Of Interest (ROI). With a resolution in the order of a few microns, defects from filament fractures and small foreign particles up to fuzz balls can be clearly marked.

1. Introduction

With the growing use of CFRP, an increasing demand for process monitoring as well as process control comes along. Typical applications for visual inspection systems focus on the fibre orientation of fabrics, non-crimp-fabrics (NCF) [1-5] or on the position and curvature measurement [2,3]. Some are also used for the detection of defects [6] such as fuzz balls, gaps between rovings, yarn splices or missing rovings. These systems are usually based on matrix camera systems or as in [6] on a scanner.
Considering online process monitoring and online process control of such production lines, the main system requirement is a wide scan area of continuous or discontinuous moving substrates at high resolutions. As an example the production of carbon fibres shall be considered. With a single filament diameter of 5 to 7 µm a resolution in the same order is necessary to detect single filament fractures, one parameter able to describe carbon fibre quality. The width of a typical carbon fibre mass production line is in the order of 2 to 3 m at a line speed of 0.2 m/s [7]. Due to the mentioned line speed and the poor reflection characteristics of the carbon fibres, sensitive image sensors, high

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acquisition rates as well as a capable illumination system are required. At high resolution the observed region becomes small in comparison to the line width. This requires a multiplication of the installed hardware, leading to a further increase in data volume. A similar challenge is related to the monitoring of binder distribution applied on a fabric, non-crimp-fabric or unidirectional carbon fibre tape. The same aspect of wide inspection range, movement of inspected matter and high resolution to derive the amount of locally applied binder leads to similar conclusions.
In scope of the above, this study is concerned, in detail, with the development of a camera system for the aforementioned application of online monitoring carbon fibre production and further briefly addresses the problems related to binder application monitoring. Providing a monitoring system scalable at economically reasonable expenses, the scan width is maximized and the speed requirements are fulfilled by the use of a line scan camera system. As a result, the system is capable of producing high resolution images at a scan width three times higher than that achievable with conventional optics, while keeping the data volume the same.

2. Layout and Experimental Setup

The principle design idea of the presented setup is the independent use of different sensor channels and an optic, capable of monitoring and simultaneously superposing different regions of interest (ROIs).

2.1. Hardware

The applied camera is an e2v Ellixa+ 8k CL, a cmos multi-line colour camera with four 8k line sensors. The sensor pixel size is 5 µm. The sensor layout (two complete lines for green and two alternating lines for red and blue) allows a resolution of 5 µm on sensor level for the green channel and 10 µm for the channels red and blue. The colour resolution is 24 bit (8 bit for each channel) and the maximum line rate is 50 kHz. For the illumination of the carbon fibres being monitored a Chromasens® Corona II led line lighting system is adopted for the test setup. For monitoring the binder application a Corona II tube lighting is used.
In addition, a high performance PC with a Silicon Software frame grabber type microEnable 5 VD8-PoCL with an extra Xilinx Virtex field programmable gate array (FPGA) and a dedicated Nvidia GPU are part of the setup.

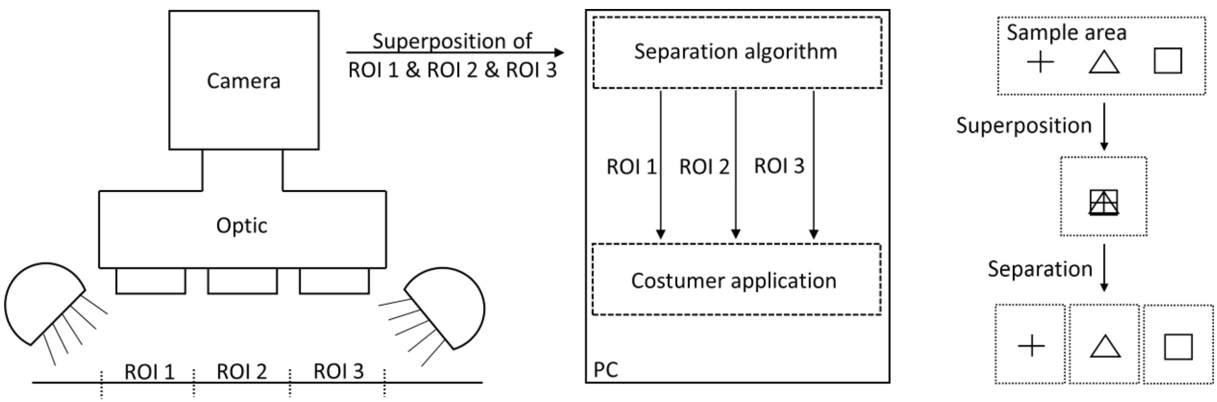

Fig. 1 The basic principle of the system setup is shown on the left. On the right side, the superposition of the image capturing and separation is illustrated.

At a maximum acquisition rate of 50 kHz, full resolution in width and 24 bit the camera sends about 6.5 Gigabit per second to the frame grabber. Therefore, the frame grabber is operated in Camera Link full+ mode. On the PC/frame grabber the data is split into single frames. These can be processed either on the FPGA, GPU or directly via the application software.

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2.2. Optical System

To increase the measured region an optical system was developed. The optical system is customizable to different vision systems, e.g. area or line scan cameras and adoptable for different resolution and field of view (FOV) combinations. The achievable factor equals three, keeping the resolution the same.

For the applicability of the principle, a camera system sensitive to different wavelength regions, is needed. By superposing the information from three different ROI in the different wavelength regions, e.g. the structural or substrate information in the red, green and blue wavelength range, the expansion of scan width can be achieved. The superposition of the different ROI is achieved by an optimal combination of lenses, filters and mirrors as depicted in Figure 1. Due to the use of filters the information from the different ROIs is captured only within the particular allocated colour range. With the mirrors the information of the ROIs is mapped to the vision sensor. As the image separation is postponed to the software or the FPGA hardware, a data transfer bottleneck is avoided.

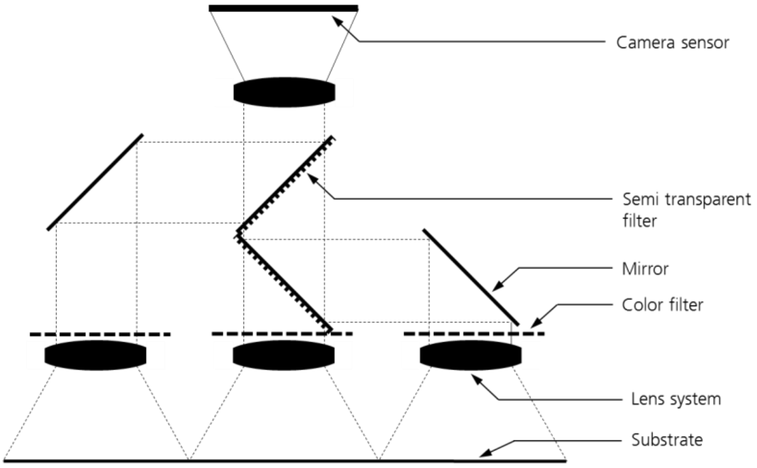

Figure 1. Schematic diagram of the optical system

Figure 2 depicts the spectral sensitivitis of the e2v Ellixa+ line scan camera for the different colour regions (lines with symbols). As can be seen, there are overlapping areas within the different wavelength sensitivities, negatively affecting channel separation. Therefore, adequate filters had to be applied. The characteristics for the filters are also plotted (dotted lines in Figure 2).

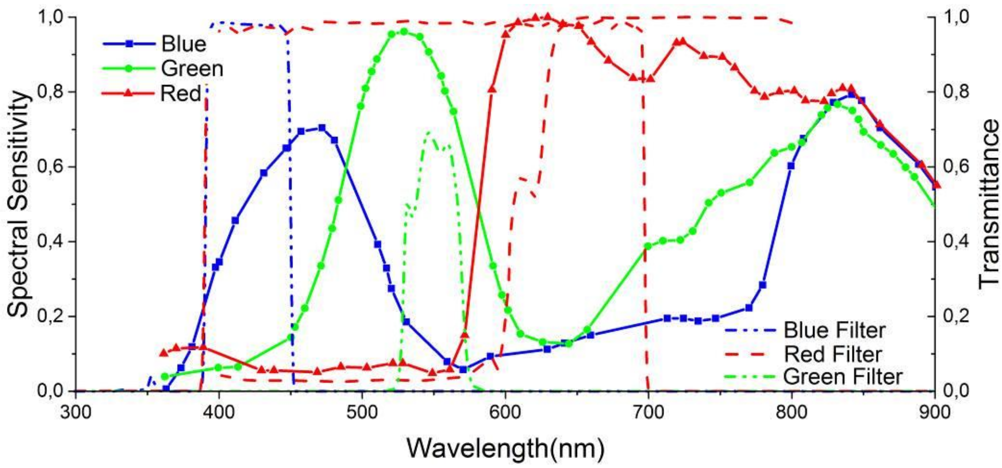

Figure 2. Spectral sensitivity of the different colour regions and the characteristic envelopes of the colour filters against wavelength.

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2.3. Software

The software runs on the .NET Framework 4.5 and was implemented in C#. The image processing algorithms are based on the HALCON library. This setup ensures meeting the performance and reliability requirements, which are mainly determined by the camera frame rate and data transfer amounts.
Usually, the incoming image data is a regular 24-bit colour image with three colour channels that equally contain colour details and must then be processed by the software. In most cases, the image is converted to a gray scale matrix and therefore only one channel is extracted from the image data. The new RGB concept merges three different scan areas in one image, using all three colour regions. Therefore, the RGB channels have to be extracted one by one prior to image processing. This allows a significant increase in scan width without the need for installing other complex and expensive hardware, such as additional cameras for example.
However, this creates new challenges for the software systems since the amount of data that has to be processed in each iteration increases. The software's performance and data management becomes more important in this scenario.

3. Analysis and Results

Preliminary investigations were conducted to select the camera settings providing optimum results.These settings were then used for further work. For CameraLink full extended configuration, the speed is up to 50 kHz and the data transfer rate is limited to 6.8 Gbit/s as mentioned in section 2.1. The optical system allows a resolution of 5 µm on the surface, with a measurement width of 120 mm, whereas standard optics are limited to 40 mm width due to data transfer reasons. To illustrate the achieved results, images of the RGB system are presented next to the images of the whole measurement range (with less resolution) in Table 1 on the example of binder application and Table 2 for the case of carbon fibre monitoring.
Row 1 in Table 1 lists the image captured with a different objective lens at lower resolution. Further, the superposed image of the marked areas is presented, followed by its decomposed images after color separation. For easier comparison, the grey images are provided. To show the processability, resulting images after a threshold application are pictured in row four.
White parts in the designated wavelength regions illustrate detected binder areas after processing. The last row of Table 1 presents the intensity distribution for each colour against an 8 bit gray value scale, with zero for black and 255 for white. The achieved gray value distribution for all three channels is comparatively similar, especially for the red and blue channels. The green channel was further processed due to the fact that the frame grabber does not completely separate the single lines. Therefore, artifacts of the other channels had to be removed.
The monitoring of misaligned filaments and filament fractures was carried out using a dark field illumination setting as a pre-stage to process implementation in laboratory scale. As can be seen in Table 2 only the disturbed areas are highlighted. For the following digital defect detection and later on the categorization this is a great benefit. The easiest way to detect the failures is the application of a simple threshold, which leads to a very fast digital evaluation. However, in most cases a more sophisticated approach such as the Canny Edge detection is needed to identify defects. As can be seen in the Table 2 – row 4, single filaments as well as larger flaws can be detected by edge detection algorithms. Similar to the presentation in Table 1 processed images are recoloured to visualize identified defect areas. As observed above, gray value distribution in the blue and red channels are quite similar, whereas the green channel is slightly different due to correction reasons.

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Table 1 Comparison of images captured by standard optics and RGB System for binder distribution monitoring.

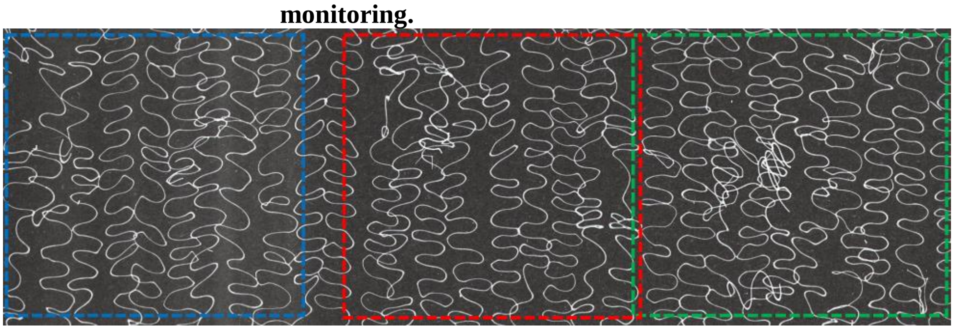
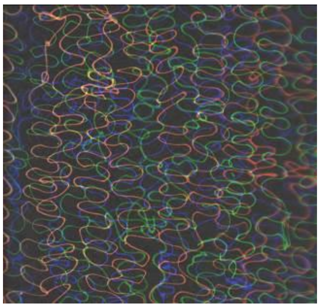
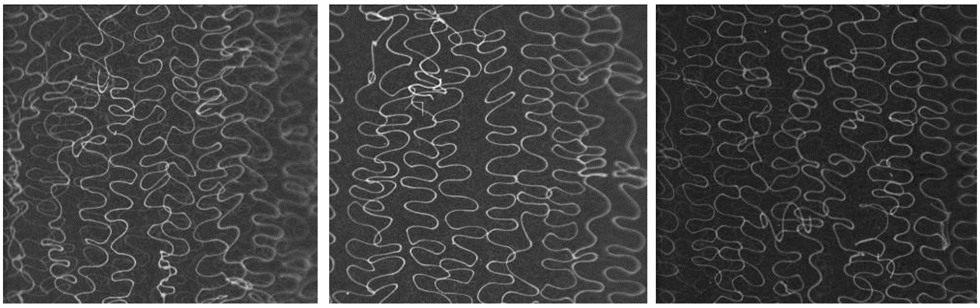
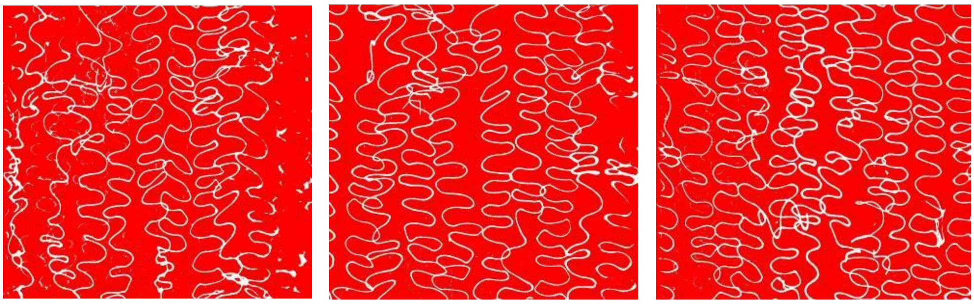
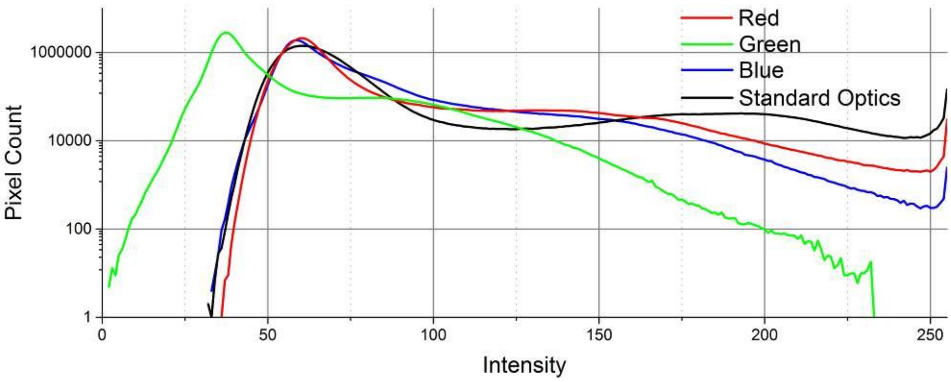
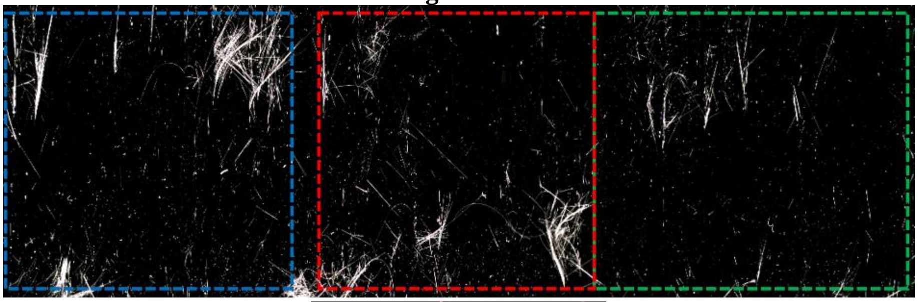
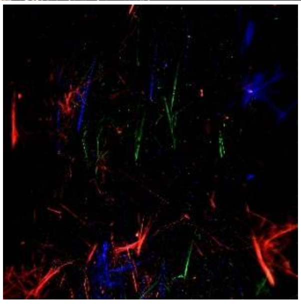
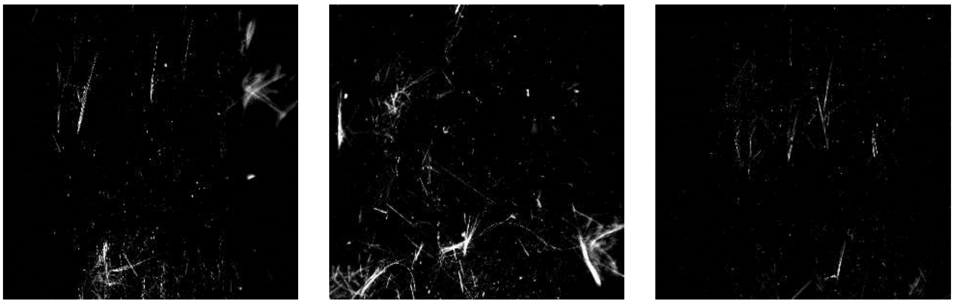
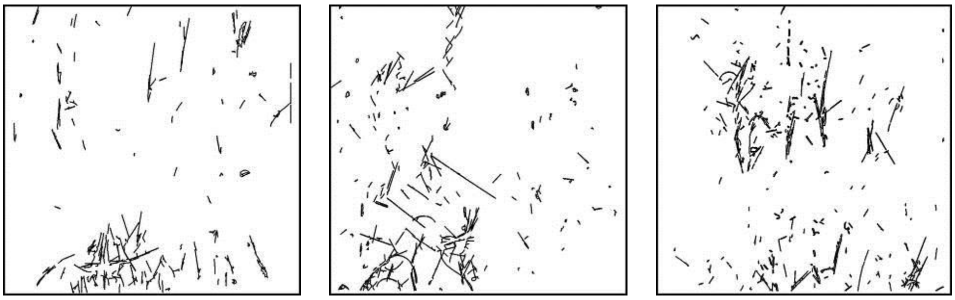
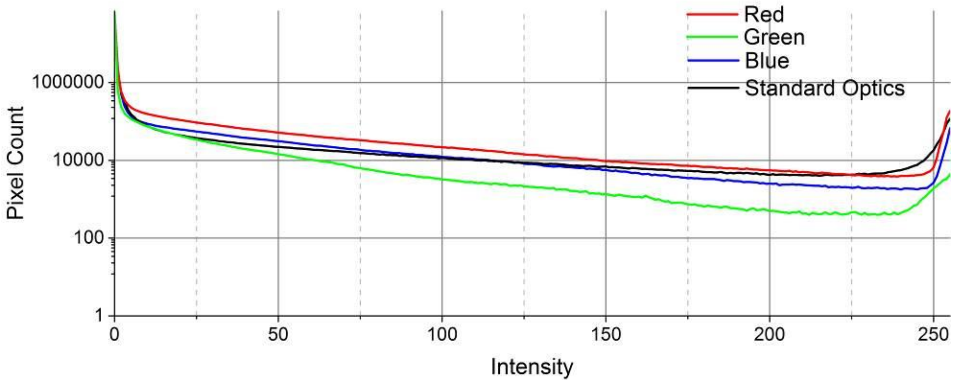
Substrate area (captured with a three times lower resolution)	
Superposed image of R/G/B colour regions	
Separated images	
Processed images	
Grey value distribution	

Table 2 Comparison of images captured by standard optics and RGB System for fibre misalignment and fracture monitoring.

Substrate area (captured with a three times lower resolution)	
Superposed image of R/G/B colour regions	
Separated images	
Processed images	
Grey value distribution	

For the specified application of failure detection during carbon fibre production the requirements are a resolution of about 5 to 7 µm and a substrate speed of 0.2 m/s. With conventional optics the system can monitor a measurement region of about 40 mm. With the developed optic system, it is possible to triple the measurement range to 120 mm at the same amount of transferred data which lies within the scope the Camera Link specification of 6.8 Gbit/s. However, in this case the limiting parameter is the light intensity brought to the sensor.

Image processing and nominal speed

The image processing unit should be able to complete each iteration within a time span depending on the camera frequency and the nominal speed of the substrate. The nominal speed is determined by the production line and equals 0.2 m/s [7]. This is the minimum value at which the image must be scanned with sufficient quality and the resulting image is processed by the CPU without exceeding real-time limits. If limits are exceeded, the software would miss one or more frames and continuous monitoring could no longer be guaranteed.

In order to show the system’s capability to monitor the substrate at this speed without interruptions, the software’s execution time was measured. This was carried out using the HDevelop profiler provided by the HALCON framework.

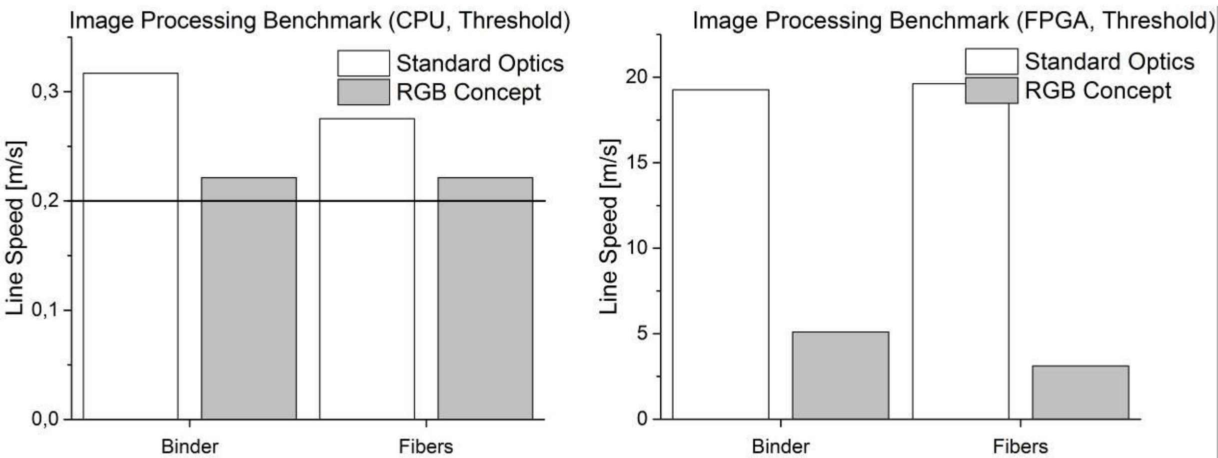


Figure 3 Comparison between image processing of fibre and binder images

As seen in Figure 3 the maximum speed that will allow the CPU a sufficient time frame to process the acquired image with auto threshold was higher than the line speed for both carbon fibre and binder samples. Therefore, the software is able to process the data within the given time limits. Figure 3 also shows the results for an estimated FPGA implementation which would speed up execution time and reduce it to less than 1 ms for each frame. The maximum tolerable line speed rises to a level that makes it negligible since it is then no longer a limiting factor.

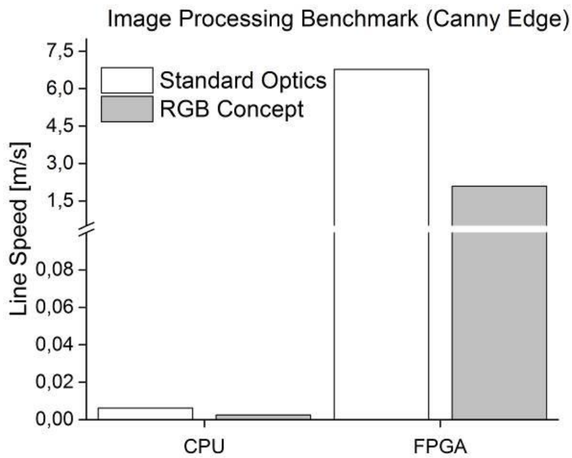


Figure 4 Comparison between execution time depending on the nominal speed for Canny Edge

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For a more sophisticated filter the execution times rises and therefore the transportation system has to lower the speed. The results for a "canny edge" implementation executed on a CPU are shown in Figure 4. The maximum fibre production line speed decreases to less than 0.05 m/s. The minimum speed required by the transportation unit can no longer be met. However, the estimated speed limits for an FPGA implementation can easily meet the real-time requirements and allow the substrate travel at the demanded nominal speed.

4. Conclusions and Outlook

As shown the basic principle of the colour separation was successfully implemented on laboratory scale for the detection of binder application as well as filament fracture and filament misalignment monitoring . Nevertheless, optimizations with respect to optical path and filter characteristics are being continued.

Special consideration was given to the image processing performance. As the requirement for real time application is one of the main challenges for data processing. For threshold computation on both binder and fibre images, real-time criteria could be met. More complex analyses such as edge detection algorithms could not be processed with the current hardware setup within the time frames given by the acquisition rate. For further work, image processing operations will be shifted to the FPGA hardware which promises considerably faster processing.

However, the actual system meets requirements of both applications of binder application as well as high resolution monitoring of defects during carbon fibre production. Due to its flexibility the use of the developed optical path is not only limited to the described implementations and can be adapted to a wide range of challenges.

The defect detection as well as the categorization will be addressed more deeply within further publications.

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