XVIII IMEKO WORLD CONGRESS
Metrology for a Sustainable Development
September, 17 – 22, 2006, Rio de Janeiro, Brazil

FEASIBLE PRODUCTION OF FIBRE-REINFORCED COMPOSITES THROUGH INLINE INSPECTION WITH MACHINE VISION

Prof. Dr.-Ing. Robert Schmitt [1], *Prof. em. Dr.-Ing. Dr. h. c. Prof. h. c. Tilo Pfeifer* [2], *M. Eng. Alexandre Orth* [3]

Laboratory for Machine Tools and Production Engineering (WZL), Chair of Metrology and Quality Management,
RWTH Aachen University, Steinbachstr. 53B, 52074 Aachen, Germany,
[1] R.Schmitt@wzl.rwth-aachen.de
[2] T.Pfeifer@wzl.rwth-aachen.de
[3] A.Orth@wzl.rwth-aachen.de

Abstract: The application of Fibre-Reinforced Plastics is important in many engineering areas, but vital for the aerospace industry. This work shows how inline metrology can contribute to a feasible production of composite parts. An inspection system based on a Machine Vision System will be presented as a key-component for the automatic construction of complex Preform structures.

Keywords: Aerospace Industry, Optical Metrology, Fibre-Reinforced Composites Inspection, Machine Vision

1. INTRODUCTION

The aerospace industry is dealing nowadays with substantial challenges. On one side, the demand on aerospace transportation is increasing continually, but on the other side, the airplane's requirements is becoming more strictly [1], specially considering its reliability, weight to dimension relation, mechanical resistance, environment protection as well as economical efficiency. In this global competitive scenario, the future of the aerospace industry lies in the hands of the most innovative companies. In this context, Fibre-Reinforced Plastic (FRP) from glass and carbon has become a strategic technology [2] because of their advanced physical properties (e.g. high specific strength, fatigue endurance, impact resistance, corrosion resistance and little thermal expansion) combined with a relative small weight. Generally, the whole transport industry (e.g. aerospace, automotive, ship, train etc.) and many other manufacturers such as for medicine, metrology or even sports equipment, are very interested to increase their products' value by the adoption of composite materials.

Textile FRP-Structures [3] consist of a set of endless fibre bundles (so-called *Rovings*), which are confectioned in a textile process to a flat component (or layer) with specific binding types. These layers are cut in pieces with different forms and sizes, depending on the reinforced structure plan. The Preforms are complex textile structures, which are built by deposing several textile layers over each other (Fig. 1). The accurate position and structural characteristics of each layer have a crucial importance for the whole product quality. The fibre alignment and the fabric structure of each textile layer will define the stiffness (parallel to fibre orientation) and elasticity (perpendicular to fibre orientation) of the final piece. Particularly, special reinforcements may be required to properly fulfil the mechanical specification at some specific zones of the product.

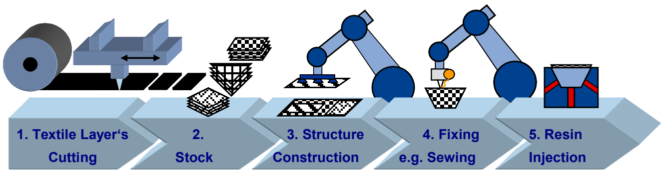


Fig. 1: Manufacturing process of Fibre-Reinforced Plastics

The Preforms production today is still accomplished mostly manually. Especially for the case of the aerospace industry [4, 5], which is characterised by a small production batch with a high complexity and variety of product parts, this non-automated production process implies considerable process dispersion and a high rework rate, which reflects in large material costs. Because of all these aspects, the production of Preforms is very complex and also cost-intensive. This is the main reason, why this technology is mainly applied for very exclusive applications or 'high-tech' products. Because of the deficiencies in appropriate manufacturing technologies [6], such as an automated handling system to control each textile layer during its placement, a fully automated confection machine for FRP is not yet available. In this case, the development of metrology for quality loops in serial production is just beginning. Therefore, considering the complexity of FRP structures as well as the challenging application requirements, only the increase of the automation level [2] can ensure a feasible production of the required high-quality product. Such a system would enable the customers to profit by the advantages of this technology in manifold products.

This work intends to elucidate how inline inspection systems [6, 7] can contribute to achieve a feasible production of Fibre-Reinforced Composites. It will focus on an inline measurement system, which is being developed at the Laboratory for Machine Tools and Production Engineering (WZL) to enable an automatic construction of complex Fibre-Reinforced Plastic structures. This inspection system is based on a Machine Vision System, which has to execute different inspection tasks on the industrial shop floor. Chapter 2 presents a short overview of the inspection technology in the FRP production process. After that, the main parts of the developed measurement system will be presented in detail (chapter 3). Chapter 4 presents a prototype for performance evaluation of the inspection system under industrial conditions. Finally, a set of conclusions and future perspectives will be drawn.

2. INLINE INSPECTION IN FRP-PRODUCTION

A large manifold of measurement systems can be applied for composites inspection, starting by traditional inspection systems for material properties [8] (such as stiffness or cohesiveness) moving to some specialized systems such as based on ultrasonic or infra-red sensors. Non destructive ultrasonic testing [9] is a very important inspection system for FRP, which can be applied to test material non-homogeneities (such as pore detection, fibre fissure or adhesive errors) or even to detect the fibre orientation. Other typical analysis methods are based on microscopy, where a piece of material is imaged with a specific beam (light, electron, x-ray, infra-red, micro-wave or even tera-hertz beams). Depending on the beam type, it is possible to detect different properties of the material. For example, x-ray beams [10] are very useful to inspect intern materials defects. Already the infra-red beams, also called thermography inspection [11], use the different thermal resistance in non-homogeneous material regions to find structure errors. Image processing can be applied to objectively quantify the collected information of all these sensors types. For example, Lee et. al. shows in [12] how to determine the final fibre orientation in composites by applying image processing techniques over a material's cut section.

But, in fact, composite materials are still a young technology, in which inspection systems are much more oriented to research purposes than to industrial production. Many of these systems need a preparation step before the inspection, which may damage the piece or are laboriously. Other characteristics are long inspection times, small measuring areas and non adequacy for industrial environments. Therefore, these methods are mostly only appropriate for the quality analysis of FRP at the end of the value creation chain, i.e. as sampling inspection after the manufacturing to adjust the process parameter (Fig. 1). For an automatic production process of Fibre-Reinforced Plastics, the following inspection tasks have to be fulfilled in order to guarantee the textile structure properties:

1. **Texture Recognition:** first it has to be automatically determined, if the right fibre material (glass, carbon or aramid) and the right structure type (multi axial layers, braids or woven fabrics) have been applied in the specified sequence.
2. **Alignment and Position:** The geometry, dimension and alignment of each textile component have to be assured; i.e. the contour position of these pieces. In this phase, handling errors occur often and, therefore, an appropriate automatic positioning control is important.
3. **Fibre Alignment:** the exact position and orientation of the textile layer's rovings has a great influence on its mechanical characteristics. The detection of the fibre local alignment during the layers' handling phases (i.e. by cutting, stocking and depositing) is fundamental for the quality and resistance of the final product.
4. **Textile Structure Errors:** errors in the textile structure, such as defect in the knitting result, generate fragile regions on the piece, which can cause a fatal damage on the FRP product.
5. **Guaranty of the Deposition Quality:** Another reason for fragile regions on the textile are deposition errors. For example, wrinkling can emerge during the deposition process. Especially, the deposition of the textile structures over a 3D mould causes a deformation on the fibre structure and thus a modification on the fibre alignment.

New developments on ultrasonic technology promise a possible inline solution with lateral scanning [6]. However this method is not suitable for the monitoring of the FVK-structure construction, but for an integrated control of material homogeneity. Image processing has been used for some time in the textile industry for error detection and also for sewing process automation [13]. Most of the inspection systems developed especially for FRP-components up to now are focussed on the measurement of the fibre-orientation and the failure detection on the textile layers [14][15]. However, the inspection of the material type, textile structure, alignment, geometry and drapery's quality of the textile layers are not yet considered. Furthermore, wide measuring areas with small measuring uncertainties, limited production cycles and high reliability are requirements still to be appropriately fulfilled, in order to match the demands of the aerospace and automotive industry. Without inline inspection systems, which are able to control these process parameters directly in the production line, it is not possible to implement a feedback control into the production process. This means, because of this technology gap it is not possible to achieve an automated production process necessary for a reliable production of complex composites structures under strict quality requirements by feasible production costs.

3. DESIGN OF THE MACHINE VISION SYSTEM

Because of this demand for an appropriated inspection technology for the Preforms manufacturing, the WZL has purposed a collaborative research project called *FALCON - Fiber Automatic Live Control* with others nine partners. This project consortium involves research institutes and industrial partners with expertise in different areas, from quality management, industrial metrology, optical measurement, camera and laser sensors, textile technology, material engineering, system integration, Fibre-Reinforced Plastics engineering as well as an end customer, i.e. Airbus. The project FALCON aims at the development of a Machine Vision System for the inline inspection of the following properties of textile Preforms:

- **material type:** automatic recognition of the fibre materials carbon, glass or aramid without disturbance from the environment (as background or dirty particles). This information is useful for the control of material flow and also for an automatic set-up of the vision system.
- **binding type:** automatic recognition of the textile structures (texture patterns) by the binding properties (fibre bundle, crossing nodes and sewing) independent of translation and orientation. There are ca. 30 different representative sample classes for the system evaluation.
- **geometry:** measurement of the geometry from each textile structure (also in case of overloaded textile layers). First of all, each textile layer has to be detected (image segmentation) and its contours have to be measured with a position tolerance of ca. ± 1 mm.
- **alignment:** here, it is important to measure the main orientation of the fibres in each textile structure (tolerance: ± 0,5 °).
- **deposition quality:** measurement of the deposition quality considering the deformation caused by the 3D form.

This Machine Vision System should inspect the quality criteria of each textile structure during the manufacturing process. This information can be fed back into an automatic handling system, building a close loop control. This inline inspection system can be applied into several phases of the production chain, as for example by the cutting of the textile layers or by the construction of the fibre structure. Because of this, this system could also be integrated into a global system for the traceability of quality parameters during the whole production chain. This fact is very important in complex manufacturing processes like the ones for composite components, where the influence and interdependency of many process parameters could not yet be well explained.

The aerospace industry requires special challenge specifications for the inspection system. In order to accurately define and validate this system, a demonstrator plant will be built up on a production cell from the partner company CTC-Airbus with a measuring area of ca. 12 m^2. The automatic inspection system should be able to control the quality parameters of whole FRP structures with up to 12 layers, with 12 m^2 per layer, inside of 4 hours cycle time (1 hour set-up and 3 hours production time). This means, the available production time per layer is 15 min. Considering, that the handling system consumes half of this time on its own, the inspection system has almost 7.5 min (450 s) to inspect a textile layer of 12 m^2. The minimal object detail to be perceived by the inspection system is a roving with a width of 0.4 mm (a sewing has 0.5 mm). The system does not need to inspect each fibre, but has to get an idea about the fibre distribution for the orientation detection. Therefore, this minimal roving width has to be sensed with a minimal resolution (5-10 pixels/roving). The contours of the textile structures, which may not be clearly defined because of noise yarns, should be detected up to an accuracy of ± 0.1 mm. Therefore, a combination of a machine vision system with a light section sensor, fusing the advantages of both sensors, is then thinkable to optimise the inspection process in terms of time and accuracy. Finally, this new inspection technology should be integrated on a portal robot of the demonstrator plant from CTC-Airbus, operating under typical industrial conditions (vibration, noise, dirt etc.).

3.1. Optical Properties of FRP-Structures

Fig. 2 shows the three material types, which are to be detected by the vision system. These objects present a great light reflection and colour variance. In the FRP production, only one material type is applied per piece. However, this information is useful for the adjustment of the vision sensor.

Fig. 2: Material types: glass, aramid and carbon fibres

Preforms are usually constructed from two main types of textiles (Fig. 3). Multi axial layers (MAL) are composed by many plan layers of parallel Rovings, which are connected to each other by bonding or sewing. MAL can be seen as flat objects, but the contrast between sewing and Rovings may be problematic. Woven fabrics are constructed by crossing the Rovings with each other under specific rules. Therefore, they do not need to be sewed. On the other side, they present a 3D topography, which is difficult for visual inspection.

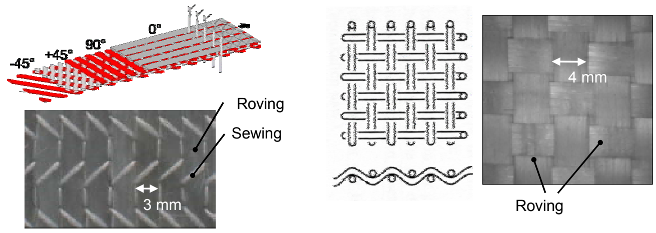


Fig. 3: Features of multi axial layer (left) and woven fabric (right)

The optical properties of these textile structures have been deeply analysed through practical tests, as shown in Fig. 4. A Roving is defined as a bundle of endless fibre yarn. A measurement with a white-light interferometer confirms this but also shows that these yarns have non-uniformity cylinder form. Fig. 4 demonstrates also how important is the light direction, where a woven fabric appears completely different with a 45° rotation to the light beam. Polarisation filters have provided benefits to enhance the properties of carbon fibre, being interesting for failure detection.

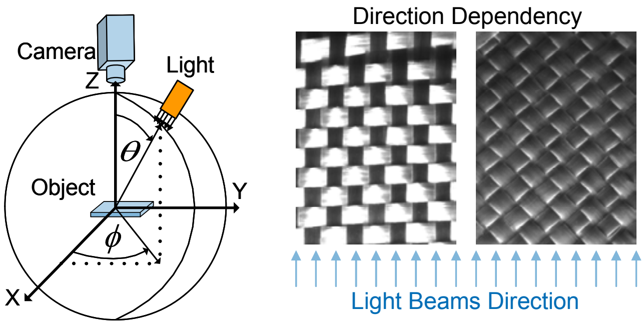
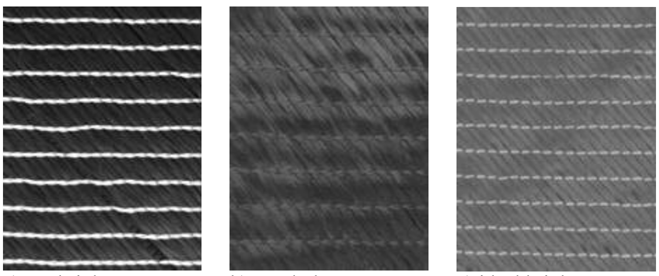


Fig. 4: Light reflectance of woven fabric depending on beam directions

3.2. Image Acquisition Strategy

An essential step for the development is to define how the object scene is to be ideally imaged in order to enhance the important object properties and to reduce unnecessary information. Thus, it is being searched for the best compromise between all components involved on the image acquisition (e.g. light, lens, camera or frame-grabber), till a digitalised image is ready for processing. First of all, each of these components has been separately analysed, where all possible features and parameters have been listed and are already roughly limited under consideration of the critical requirements. Secondly, the interdependency of these components has been modelled and simulated to achieve a global optimum. For example, the influence of the camera resolution on the inspection time, frame-rate and transfer rate could be determined for a fixed accuracy of ± 80 µm. This analysis proved, that at least a camera with 8 Mega-Pixel has to be applied for the given inspection task. The depth-of-field and other optical or camera properties have been defined, which will be used by the project partner Basler to develop a camera sensor specialized for this application.

The illumination technique plays an essential role for this Machine Vision System. All illumination possibilities have been analysed systematically according to their light source (e.g. spectrum, diffuse or polarised), direction (e.g. bright or dark field) and geometry (e.g. dome or ring light). The nine interesting illumination strategies have been tested with a practical assay (Fig. 4) and evaluated in the following five criteria: reflection behaviour, non-homogeneity, direction dependency, contrast between sewing and roving (MAL) and creation of texture pattern (woven fabric). The major difficulties were how to avoid image saturation on the sewing areas (Fig. 5) and how to diminish the pattern formation by woven fabric. A strong axial diffuse illumination combined with a lateral one (in dark field) has been verified as the best solution for these inspection requirements (Fig. 5.c). This illumination has been implemented with high frequency fluorescent light with daylight spectrum (Fig. 10).

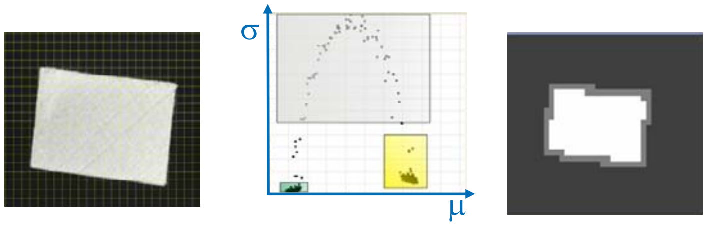


a) too bright b) too dark c) ideal brightness

Fig. 5: Illumination influences on the contrast sewing to fibre

3.3. Image Processing Algorithm

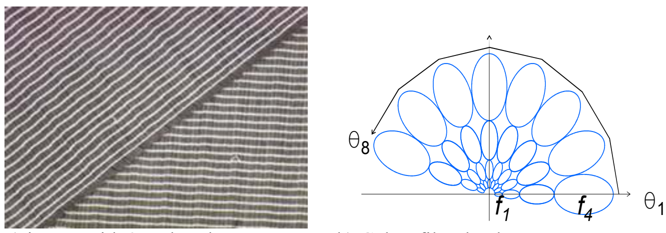
The textile structures are characterised by a periodic texture pattern with some brightness fluctuation depending on the illumination conditions. Because of this, the image processing algorithms required for the inspection system are based on texture analysis [16]. The first inspection task, the material recognition, has been implemented using local statistic parameters (mean, variance and range value) as texture features. The algorithm recognizes the three materials plus the background and transition areas (corners, Fig. 6).



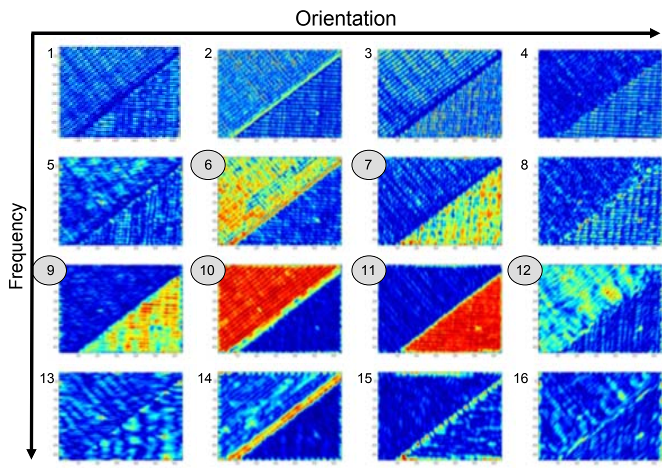
a) image raster b) local statistics c) segmented image

Fig. 6: Algorithm for the material recognition

The second step is the separation of the textile layers on the measurement area. This task has been accomplished by applying a texture segmentation algorithm based on Gabor filter banks [17]. A Gabor filter can be seen as a Fourier analysis, which is magnified through a Gabor function over a neighbourhood, such as a local Fourier analysis. By convolving this Gabor filter over an FRP image, the filter response will achieve a higher intensity, when the filter frequency and orientation comes in resonance with the texture pattern. By varying these parameters, a filter bank is built up for different situations. The algorithm selects the most significant filter response according to the image variance (in case of Fig. 7, the responses 6, 7, 9, 10, 11 and 12), whose pixels are classified by a K-Means Clustering method [17] as an image with n-dimensional pixel values (colours). Fig. 8 shows the segmentation result in an image with three different textile layers. A small error can be seen on the border areas, which is quite normal, since texture is defined via a neighborhood relationship.



a) image with 2 carbon layer b) Gabor filter bank



c) Gabor filter response in different orientation and frequency spectrum

Fig. 7: Algorithm for unsupervised texture segmentation

The recognition of the binding type occurs based on the Gabor filter features. Fig. 9 shows the Gabor filter features calculated from two images of a textile layer, once in 0° and another in 45° rotation. It can be noted, that the rotation of the pattern generates a translation in the Gabor features (Fig. 7.b and Fig. 9). By calculating the Fourier Transformation of each row of the Gabor features, a rotation invariant parameter vector could be defined, which allows a correct classification of the binding types. Further algorithms for the detection of main orientation and deposition quality control of textile layers are now under development.

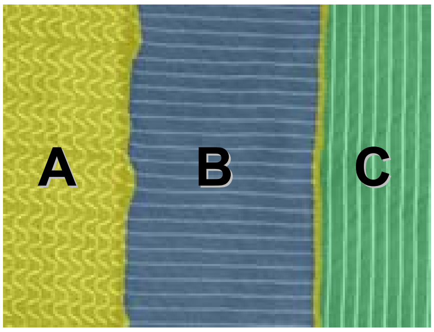


Fig. 8: Segmentation result of an image with three textile layers

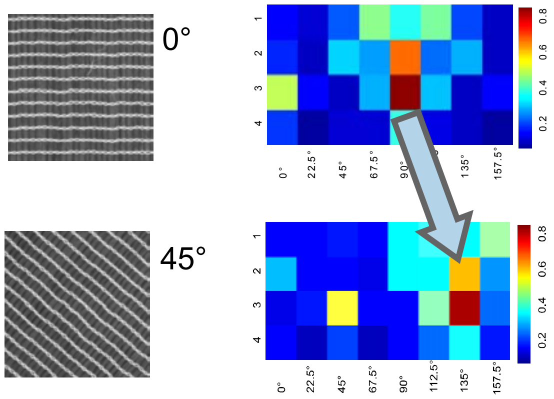


Fig. 9: A pattern rotation generates a translation in Gabor features

3.4. Laser Light Section Sensor

In order to detect the contour position of the textile structures accurately, a laser light section sensor will be applied for a fine contour detection. In this case, the laser turns the different heights of two textile layers visible by projecting a line over it. A camera detects the laser as a step profile. The best contour position is defined by interpolating a polynomial function over this profile and calculating the points, where the second derivate is equal to zero. Previous measurements [6] confirm this principle with positive results for textile layers of glass and aramid fibres. However, the reflection behaviour from carbon fibres as well as the interference of yarns and sewing on the measurement data requires the development of specialized laser sensor for this application. This technology will be developed together with the project partner NoKra.

4. FALCON PROTOTYPE

A Machine Vision Prototype is being built presently at the WZL for inline inspection of FRP textile structures (Fig. 10). This system consists of three linear positioning axes, a motorised lens, a colour camera, a PC with Pentium IV 2.6 GHz Processor and a user friendly interface. Furthermore, four illumination strategies have been built up to provide flexible illuminations conditions: an axial, a 45º directional, a dark field and a back light. Most of the images here have been acquired using this prototype. The prototype allows a rough analysis (resolution of ± 0.9 mm) of a large field of view (676x522 mm by an 764x574 pixels image) at the upper position and a fine analysis (resolution of ± 0.07 mm) of a small field of view (54x40 mm) at the down position. This prototype offers an ideal development platform for this research project, where all methods presented above are being implemented and validated.

Fig. 10: FALCON Machine Vision Prototype

An automatic inspection process is being implemented in the prototype's software. First, an image of the whole measuring area is taken with low resolution and it is segmented according to the different textile layers by means of texture features. A high resolution image is then acquired from each layer to extract rotation invariant texture features, which are used for the recognition of the binding type. The rough contour coordinate of each textile layer obtained by the segmentation are used as scanning path for the laser sensor, so that the contour position can be accurately extracted. These contours are processed to measure the position and geometry of each textile layer. Finally, the texture features are also analysed to calculate the main orientation of each layer. The methods developed for this inspection system are being validated isolated and later on they will be tested together with the automatic inspection process. For example, the image segmentation algorithm has been tested with more than 200 samples and has provided a quality rate over 97% right segmented pixel (errors on corners).

5. CONCLUSIONS AND PERSPECTIVES

In the current global competition scenario of the aerospace industry, Fibre-Reinforced Plastics (FRP) are a vital technology to achieve light-weight products with even better material properties such as mechanical resistance. However, the deficit on adequate manufacturing systems for composite structures is retaining this revolution. A reduction of manufacturing costs and an increase of the production lot are essential to expand the market of Fibre-Reinforced composites. However, this can only be achieved by an automation of the handling and inspection processes.

A Machine Vision System for inline inspection of textile structures, which has been presented in this work, aims at a traceability of quality criteria during the whole process chain of Fibre-Reinforced Plastics. Process deviations related to the textile structures can be avoided by means of a real time feedback control with an automatic handling device. This inspection system guarantees an accurate construction of Preforms by automatically controlling the material type, the binding type, the geometry, the alignment and the deposition quality of each textile layer. This work has shown how an appropriated image acquisition strategy can enable the visual inspection of different composite properties. The amount of required inspection tasks needs the development of different image processing algorithms, which could only be discussed here briefly. However, these methods will be described in more details in future publications. The combination of a vision system with a laser sensor promises to be a good strategy for a suitable industrial inspection system under the purposed requirements. The inspection system prototype at WZL enables the improvement and validation of the developed methods under real industrial conditions.

These efforts advance the production of complex fibre structures to higher product quality by lower scrap quota. Consequently, the range of economically producible FRP products can be increased as well as new market segments with cost sensitive products can be attended. Solely in Europe, a market growth of 9% per year of FRP applications in the aerospace industry is expected. All these arguments prove how metrology can enable a feasible manufacturing of high valued-added composite parts, representing an essential technology for a sustainable development in many areas, for example as a vital instrument for the aerospace industry.

ACKNOWLEDGMENTS

This work is funded by means of the collaborative research project *"FALCON - Fiber Automatic Live Control"* (http://falcon.wzl.rwth-aachen.de) in the funding program *"InnoNet"* from the German Federal Ministry of Economics and Technology (BMWi) with VDI/VDE-IT. We gratefully acknowledge for this support as well as for the active cooperation of all project partners: Institut für Textiltechnik der RWTH Aachen (ITA), Faserinstitut Bremen e. V. (FIBRE), Basler Vision Technologies (Basler AG), NoKra Optische Prüftechnik und Automation GmbH (NoKra), Gimpel Ingenieur-Gesellschaft mbH (Gimpel), Invent GmbH, Advanced Composite Engineering GmbH (ACE), Advanced Fiber Placement Technology BV (AFPT) and Composite Technology Center Stade GmbH (CTC-Airbus).

REFERENCES

[1] K. Michaels, "Plane Percentages, Composite Design", Aerospace Testing International, Ukip Media & Events, pp. 98-99, Germany, March, 2006.

[2] M. Bannister, "Challenges for composites into the next millennium – a reinforcement perspective", in Composites Part A: Applied Science and Manufacturing, Elsevier Science, Vol. 32, pp. 901-910, 2001.

[3] A. S. Herrmann, „Produktionstechnik für große CFK-Strukturen", in Industrie-Management, Vol. 6, 2004.

[4] J. Brandt, A. Geßler, J. Filsinger, "New approaches in the textile and impregnation technologies for the cost effective manufacturing of CFRP aerospace components", Congress ICAS, pp. 634.1-634.9, 2002

[5] H. B. Dexter, "Development of Textile Reinforced Composites for Aircraft Structures", 4th International Symposium for Textile Composites, Japan, 1998.

[6] R. Schmitt, P. Hafner, A. Orth, "Analysis of Current Approaches for Automatic Measurements of Reinforced Composites", In: Proceedings of the 38th CIRP International Seminar, Florianopolis, Brazil, Mai, 2005.

[7] T. Pfeifer, "Production Metrology", Oldenbourg, Munich, Germany, 2002.

[8] G. Menges et. al., „Werkstoffkunde Kunststoffe", 5th Edition, Carl Hanser, Munich, 2002

[9] T. Pfeifer, M. Benz, J. Dahmen, M. Mutz, „Qualität und Wirtschaftlichkeit – Risikomanagement, Bauteilprüfung und Kosten/Nutzen-Bewertung", in Industrielle Anwendung der Faserverbundtechnik IV, SFB 332 Abschlusskolloquium, pp. 129-137, Aachen, Germany, 2001.

[10] O. Bullinger, K.-W. Harbich, G. Busse, "X-Ray Refraction Topography of Impact Damage of CFRP Laminates", Proc. of the 11th Inter. Symp. on Nondestructive Characterization of Materials, Berlin, Germany, 2002.

[11] N. P. Avdelidis, B. C. Hawtin, D. P. Almond, "Transient Thermography in the assessment of defects of aircraft composites", In: NDT & E International, Vol. 36, Issue 6, pp. 433-439, 2003.

[12] Y. H. Lee et al, "Characterization of fiber orientation in short fiber reinforced composites with an image processing technique", In: Material Research Innovations, Springer, Vol 6., N. 2, pp. 65-72, Germany, 2002.

[13] J. Feldhoff, „Texturbasierte Bildsegmentierung am Beispiel der Steuerung von Handhabungsprozessen für das automatisierte Nähen", Dissertation RWTH Aachen, Shaker, Aachen, Germany, 2001.

[14] M. Schneider, K. Edelmann, U. Tiltmann, "Quality Analysis of Reinforcement Structures for Composites by Digital Image Processing", in: 25th International SAMPE Europe Conference, Paris, France, 2004.

[15] A. Hermann, M. Book, G. Dressler, J. Piepenbrock, „Verbundprojekt PRO-CFK", Tagung der Deutsche Gesellschaft für Luft- und Raumfahrt, Germany, 2004.

[16] R. Schmitt, A. Orth, B. Damm, "A knowledge based method to evaluate image processing algorithms - a case sample with texture analysis", EOS Conference, World of Photonics Congress 2005, Munich, Germany, 2005.

[17] A. K. Jain, F. Farrokhnia, "Unsupervised Texture Segmentation Using Gabor Filters", In: Proceedings of IEEE International Conference on Systems, Man and Cybernetics, Los Angeles, USA, 1990.