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Accurate fibre orientation measurement for carbon fibre surfaces

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ABSTRACT

Carbon- and glass fibre materials exhibit challenging optical properties, in particular highly specular reflectivity. State of the art vision-based sensor systems use diffuse light setups to suppress specular reflections and apply texture analysis to obtain fibre orientations for surface patches.

We investigate the reflection behaviour of fibrous materials. The derived reflection model is the basis for a sensor system that directly measures fibre orientation as well as diffuse and specular reflectivity per pixel. The proposed sensor is robust to changes of the fibre material and capable to deliver fast and accurate information about fibre direction without time consuming texture analysis. An empirical evaluation shows that the root mean squared error of calculated fibre angles is around or below 1°.

1. Introduction

The automatic inspection of woven material and fabric has been investigated from the early days of machine vision [1]. Texture analysis is the main tool used for segmentation, classification and defect detection on such materials [2]. Recently the topic has gained more attention due to the increase of carbon fibre and glass fibre parts in industrial manufacturing [3]. These materials, however, have very difficult optical properties due to their specular reflection and – in case of carbon fibres – high absorption of light. Traditional machine vision methods try to deal with these effects by using diffuse lighting to suppress specular reflection and generate homogeneous images [4]. However, at the same time also the contrast of important textural characteristics is reduced, which makes the analysis sensitive to noise, small material variations or illumination.

Of particular relevance in carbon and glass fibre parts production is the measurement of the fibre orientation relative to the part. The parts have highly anisotropic mechanical properties and the fibres are aligned to fit to the particular forces that are expected to act on the part [5,6]. It is thus of high importance to ensure that fibres are oriented as has been planned, which requires automatic methods for quality control [7].

In this paper we propose a vision-based approach for fibre-angle measurement that uses a new method for analyzing the images in order to obtain precise fibre orientation measurements. We will first review the state of the art of different methods for determining dominant orientations in textures. We proceed with the investigation of reflection properties of carbon fibres. Based on the derived reflection model we introduce a sensor system and algorithms for performing fibre-angle measurements on carbon fibre materials. Finally, we present a detailed investigation of the measurement accuracy that we achieved using the presented method.

2. Texture orientation estimation

The basic approach to determining principal orientations in textured images is to use the covariance matrix of the gradient vectors [8] in a local neighbourhood. The assumption is that the texture has significant contrast and a “line-like” structure, so that the gradients can be assumed to be perpendicular to the main direction of the texture. A similar approach is based on the directional evidence accumulation [9]. After converting the original image to an edge image the local dominant orientations are computed for non-overlapping sub-windows and used to increment a histogram of orientations. The maximum peaks are chosen from the histogram, assuming that the highest peak defines the orientation of the texture. A similar approach is used by Miene et al. [7].

In the field of texture analysis scale and orientation are often jointly evaluated in order to obtain algorithms that are invariant to changes in scale and orientation. Chang and Fisher [10] propose texture analysis based on Gabor filters and steerable pyramids. Their approach builds upon the assumption that features change smoothly in order to interpolate between the discrete results of the single filters.

Regarding the application of texture analysis methods for calculation of carbon fibre angles, Schmitt et al. [3] have recently

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shown to reach a measurement uncertainty of 0.4° at a confidence level of 95%. They analyze the power density spectrum for an image patch of 128 × 128 pixel acquired under diffuse lighting for dry materials.

With respect to measuring fibre directions in carbon fibre parts, there are two main challenges that have not yet been adequately addressed. Firstly, the line-like structure of the fibres has very low contrast and requires high resolution in order to be visible in the image. The visibility of these structures is also sensitive to the illumination and to the type of material. This makes it difficult to apply edge- or gradient-based methods. Secondly, woven material consists of a dense grid of regions with different orientations, which causes problems whenever larger neighborhoods are used for the analysis as the neighborhood will often contain regions with multiple fibre orientations. Computational effort is also a problem with these methods in real world applications.

A method would be preferable that provides an orientation per pixel, requires low computational effort, and works well for different types of materials. In the following sections we present a method based on photometric stereo that fulfils these requirements to a high degree.

3. Reflection properties of fibre material

Before we explain the details of our approach, we present some experimental results on the reflection properties of carbon fibre material. Reflection properties of some material are typically described by a bi-directional reflectance distribution function (BRDF) [11,12]. This function represents the amount of light which is reflected by some surface for different configurations of light- and camera-positions. These configurations are described in terms of polar and azimuth angles w.r.t the surface plane of both light source and camera. Hence, the domain of a BRDF is four-dimensional.

For analyzing the reflection behavior of carbon fibre material, we performed a set of experiments where interesting subsets of the BRDF were sampled. We used two rotation modules to rotate a light source (a high-power LED) by azimuthal and polar angles relative to a carbon fibre sample. Viewing direction of the camera was fixed for each experiment at an angle close to 45°. Fig. 1 shows a sketch of the experimental setup. Azimuth angle α was iterated in steps of 3.16° from 0° to 180°. Polar angle β was iterated in steps of 0.85° from 0° to 75°. Fig. 2 shows the amount of light reflected towards the camera (in terms of pixel grey values) for different angles of incoming light. It is clearly visible that the carbon fibre material shows very little or no reflection for most directions of incoming light (black region). However, there is a set of light positions from which light is well reflected towards the camera (bright region). The pattern of strong reflection can reasonably be described by a reflection cone. The observed fibres are aligned with the symmetry axis of this cone.

A BRDF measurement was also done for a single carbon fibre. For this, the fibre was draped over a hole in black plastic material (Fig. 3). The hole assures that the amount of light reflected from the background is kept at a minimum.

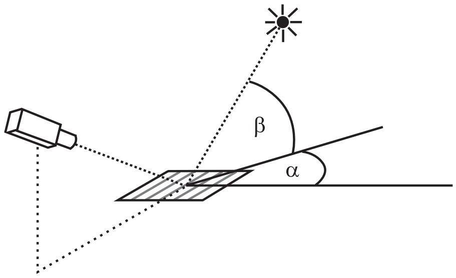

Fig. 1. Laboratory setup for BRDF measurement: two rotation modules are used to position an LED light source.

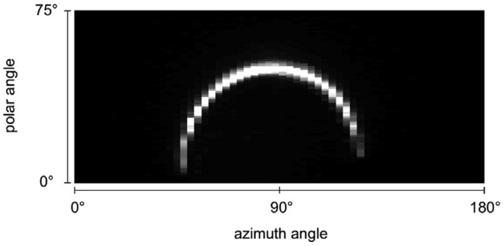

Fig. 2. Pixel gray value over different incoming light directions.

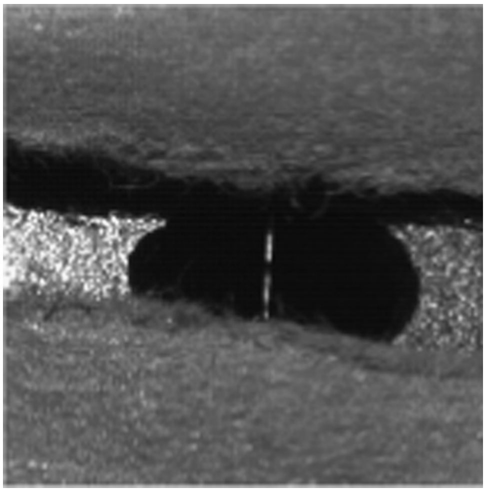

Fig. 3. Setup for BRDF measurement of single fibre.

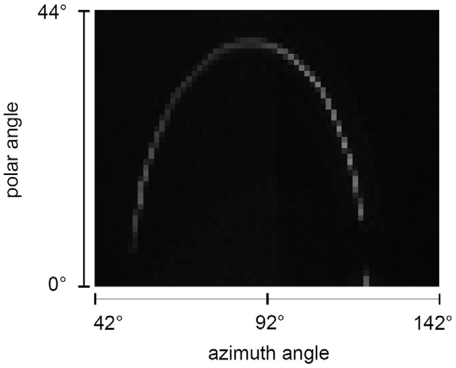

Fig. 4. Intensity of reflected light from different light source positions.

The outcome of this measurement is shown in Fig. 4. The reflection pattern is similar to the one observed for dense carbon fibre fabric (Fig. 2). In order to evaluate how well the reflection is approximated by a cone, we fit a circle to the data. Light positions of maximum intensity per polar angle are used as BRDF data points. Each point is converted from azimuth/polar representation to Cartesian coordinates at positions on the unit sphere. Fig. 5 shows these points together with the circle that is fit to this data. The root mean squared error between BRDF points and perfect circle is 0.59°.

A direct comparison of reflection profiles of carbon fibre material and single carbon fibre is shown in Figs. 6 and 7. Both figures show reflected intensity at different azimuth angles (with step size 1.6°). The polar angle was fixed to 25°. According to the cone-shaped reflection model there are two light positions where strong reflection towards the camera is observed. These peak