Texture based algorithm for analysing defects and fibre orientation of fibre reinforced plastics

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Abstract
Fibre reinforced plastics (FRP) are one of the leading materials for the future due to their stability and lightweight. Because of their inner structure, 3D texture analysis is one appropriate tool for analysing defects and fibre orientation. The adaption of a 2D texture based split and merge algorithm to a 3D version has shown promising results by evaluating computer tomography data of fibre reinforced plastics. First tests have proven that the algorithm is able to detect errors and defects as well as fibre orientation.

Keywords: computer tomography, fibre reinforced plastics, texture analysis, split and merge, segmentation, 3D

1 Introduction

1.1 Fibre reinforced plastics

Fibre reinforced plastics are made of plastic in which fibres are inserted for more stability. The fibre materials used are preferably of carbon or glass, and sometimes of aramid. So fibre reinforced plastics are both lightweight and stable which makes them particularly suitable for automotive and aircraft industry [1].
The most detailed information on the quality of fibre reinforced plastics is achieved by computer tomography (CT). CT technology provides 3D information on the inner structure (e.g. the fibre orientation) as well as on inner defects. In order to analyse these 3D data sets 3D texture analysis is an appropriate tool.

1.2 Texture Analysis

1.2.1 Texture Analysis in 2D

One common definition says: "An image texture is described by the number and types of its primitives and the spatial organization or layout of its primitives" [2]. In 2D image processing the primitives are pixels and the types are their grey values or colours. The spatial organization refers to the term structure. Structures and patterns are the way the human eye recognizes texture. Defects can be seen as deviation from the basic structure. This property of texture is already used in 2D image processing for automatic defect detection [3], as can be seen in the pictures below (see Figure 1 and Figure 2).

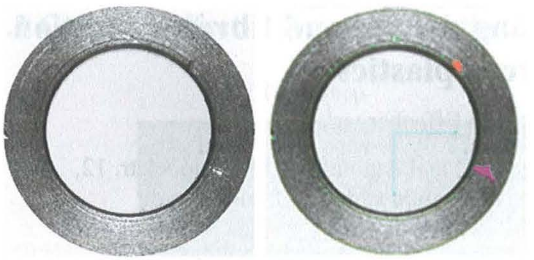

Figure 1: Image of industrial part (left), detected impact damages (right)

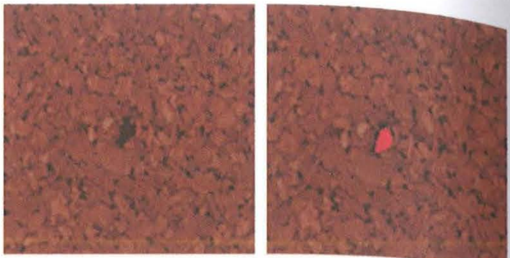

Figure 2: Image of cork tile (left), detected defect (right)

1.2.2 Texture Analysis in 3D

The basic structure of fibre reinforced plastics is defined through the fibres and their spatial organisation. Defects are deviations of this basic structure. This makes texture analysis a very useful tool for checking the quality of a fibre reinforced plastic product.

For analysing the whole product and not only the surface, a 3D image (voxel volume) is created by a CT scan. In this case the primitives are now voxels, and no longer pixels, and the spatial orientation is extended to three dimensions.

For this purpose a new 3D algorithm has been developed, based on a 2D algorithm of Chen and Pavlidis [4]. Its basic idea is to split the voxel volume first into small volume parts. The size of the small volume segments depends on the minimal size of the error or property which should be detected or analysed. Here it should be kept in mind that texture depends on the spatial variations of grey values. This means, if the volume segments are chosen too small, it will not be possible to determine the texture. A single voxel or pixel has no texture.

In the next step the texture of each segment is compared to the texture of the segments in its neighbourhood. If they have similar texture the parts are merged to a new volume segment. By continuing this process one receives in the end a texture segmented 3D voxel data set. In contrast to the basic 2D algorithm several additional requirements had to be fulfilled in the new 3D version in order to reach useful results. One of the challenges was to handle big files in appropriate time, while considering the spatial requirements of a three dimensional texture.

1.2.3 Co-occurrence Matrices

To measure the texture of volume parts co-occurrence matrices are used. In these matrices the numbers of changes in grey values of neighbouring parts are stored. This means that at first a definition of neighbouring parts has to be made. For a 2D image this can be for example: a pixel A is a neighbouring pixel of another pixel B if and only if pixel B is right adjacent to pixel A. In this case the parts are pixels and neighbours of one pixel are only right adjacent pixels. Other "neighbouring" pixels are not considered. So the grey value change to be counted is the change of the grey value of pixel A to pixel B. The number of the row of the matrix stands for the grey value of pixel A and the number of the column stands for the grey value of pixel B. So the number of the columns and rows is defined by the number of different grey values. In the following example, I is a binary image and C is the corresponding co-occurrence matrix. Only right neighbour pixels are considered. If each value of the co-occurrence matrix C is divided by the number of possible grey value changes, one gets another definition of co-occurrence matrices (in the example this kind of co-occurrence matrix is called C_n). This variant of co-occurrence matrices stores the probability and not the number of grey value changes. So each element of the matrix describes the probability of a grey value change.

Example (cf. [3])

$$I = \begin{matrix} 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \end{matrix} \Rightarrow C = \begin{pmatrix} 5 & 2 \\ 3 & 2 \end{pmatrix} \Rightarrow C_n = \frac{1}{12}\begin{pmatrix} 5 & 2 \\ 3 & 2 \end{pmatrix}$$

In most cases not only one neighbour is considered. Especially in 3D, different spatial directions have to be used to define the neighbours of one voxel. Nevertheless even in 3D the co-occurrence matrix stays two dimensional, because only grey value changes are considered and the spatial alignment of these values have just an indirect influence on the matrix.

With these matrices the calculation and mathematical comparison of textures of different volume parts is possible.

2 Results

The implementation of the above described 3D texture analysis algorithm shows promising results for automatic defect detection and analysis of fibre orientation. All 3D volumes shown in this section have been provided by RayScan Technologies GmbH.

2.1 Defect Detection

In Figure 3 (on the left side) a slice through a 3D volume data set of a fibre reinforced plastic part with some cracks is shown. These cracks are defects which affect the stability and usability of this part. The texture of the whole volume (not only one slice) has been analysed. The result is also visualised in Figure 3 (on the right side). The colours correspond to the number of neighbouring segments with different texture. This means the more right the colour is located on the scale, the higher is the textural heterogeneity. Vice versa the more left the colour is located, the higher is the homogeneity of the texture.

The result shows an obvious correlation between texture difference and the cracks in the part. So it is possible to detect the position and size of cracks by 3D texture analysis.

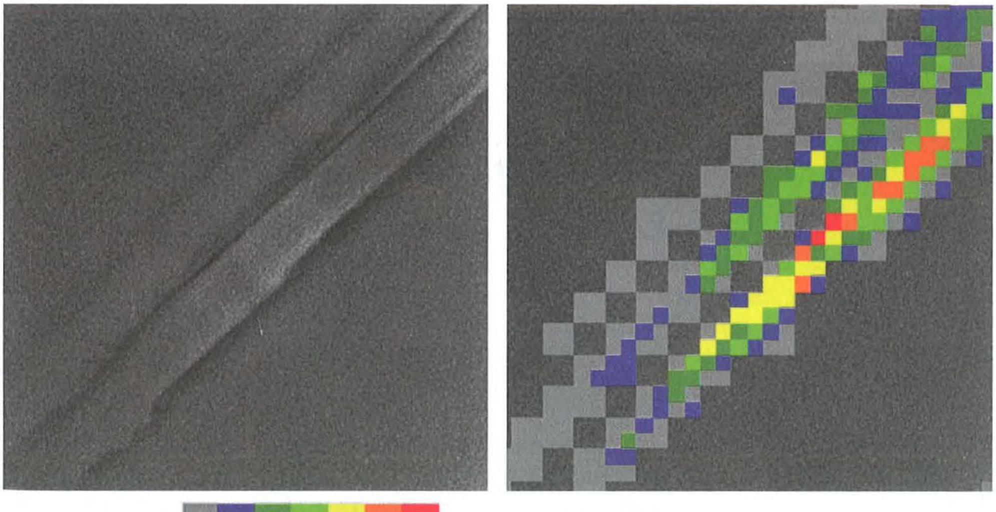

Figure 3: Slice through volume data of FRP part (left), marked texture difference (right)

2.2 Fibre Orientation

Not only defects like cracks can affect the properties of fibre reinforced plastics. Fibre orientation is one of the most important product information. The right or wrong orientation has immense positive or negative effects on the stability of the part.

The most common way to determine fibre orientation is the calculation of the Hessian Matrix for each voxel. After that the Eigenvalues of the matrices are used to determine the fibre orientation. The size of the Eigenvalue corresponds to the curvature in the direction of the associated Eigenvector [5]. This approach has been used for example by Salaberger [6].

It turned out that 3D texture analysis is another possibility to detect fibre orientation. Here the fibre orientation is extracted by determining the orientation of the resulting segments at the end of the split and merge algorithm. The orientation of these segments corresponds to the orientation of the fibres. The reason for this lies in the fact that the texture is homogenous along the fibre orientation and is broken between different fibres or rovings (bunch of fibres).

In contrast to the common Eigenvalue method no single voxels have to been considered. It wouldn't even make sense to consider a single voxel for a texture based algorithm, because (as mentioned above) a single voxel has no texture. The used algorithm analyses the structure resulting from the orientation of the fibres and not the fibre orientation by itself (the smallest volume segment has to fit to the smallest structure part). This leads to the assumption, that this approach is more adequate for data sets with less resolution and for analysing the orientation of fibre rovings, than the classic method.

But also for data sets with high resolution, satisfying results are achieved, as the following example shows. In Figure 4 (on the left side) a fibre reinforced plastic cube is shown. The extracted orientation is shown in the same figure (on the right side). The correlation between the extracted information and the real orientation can be seen even more clearly if a slice through the cube (Figure 5) is inspected.

The meaning of the colouring is listed in Table 1. Even if in this example the focus is on the axes of the coordinate system, it is in general possible to analyse any spatial orientation.

This data set mainly consists of two fibre orientations, which is reflected by the quantitative result. The algorithm isn't yet optimised for determining the amount of fibre orientation. In principle this task can be solved even though it is questionable if results are of special interest. For practical use it might be much more important to recognise and visualise deviations from given orientations, which can have an impact on the stability of a part in a given direction.

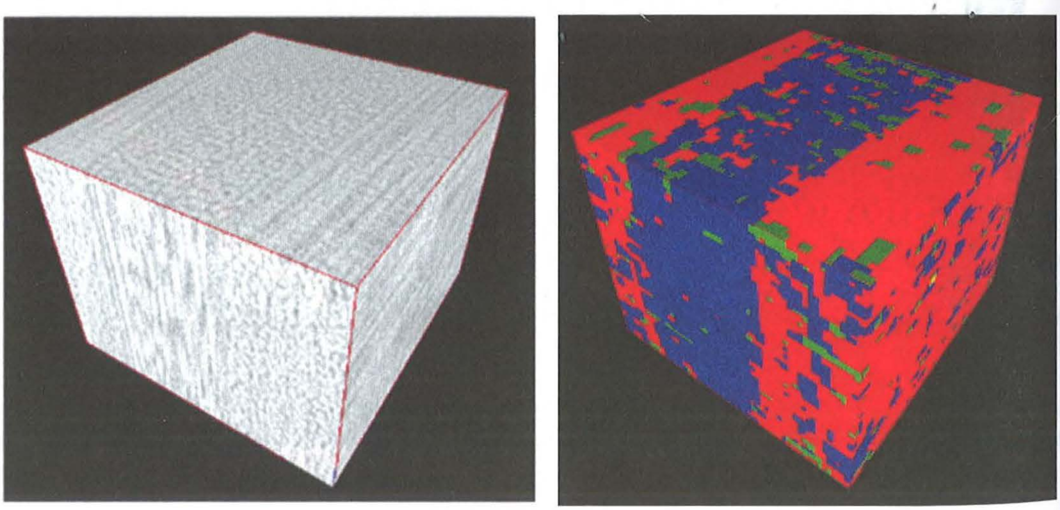

Figure 4: 3D View on FRP cube (left), marked orientation (right)

	Orientation in direction of...
	...x-axis
	...y-axis
	...z-axis
	...(1,0,1) or (1,0,-1)
	...(0,1,1) or (0,1,-1)
	...(1,1,0) or (1,-1,0)
	...(1,1,1), (-1,1,1), (1,1,-1) or (-1,1,-1)

Table 1: Colours describing fibre orientation

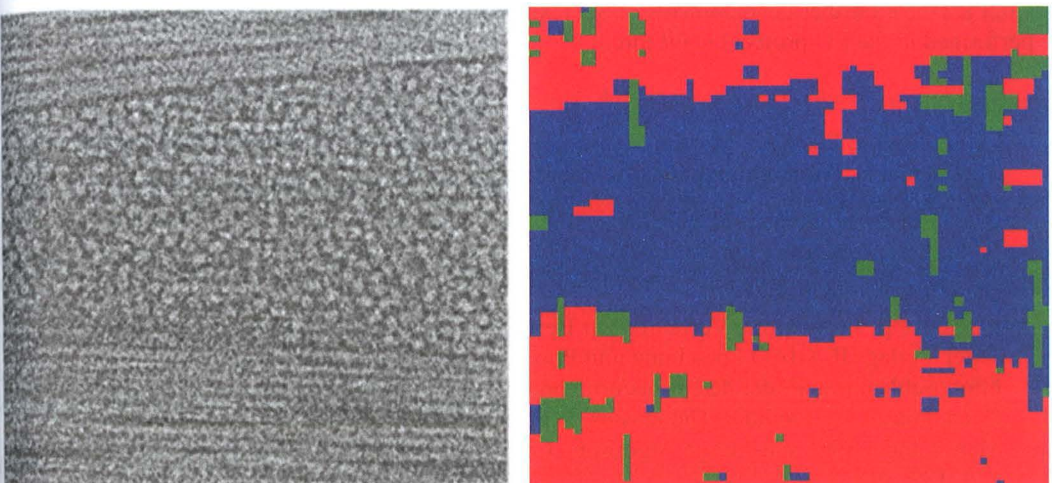

Figure 5: Slice through cube (left) and orientation (right)

2.3 Runtime and Technical Data

The tests have been performed on a Windows 7, 64 bit, Intel Core i7-2620m, 2,7 GHz PC with 4 Giga Byte ram. The runtime for the shown examples is listed in the following table. Considering the complexity of the analysis and the size of the data file an acceptable runtime has been achieved. The values show also, that the runtime doesn't increase linearly with the size of the files. The runtime depends on the ratio between the smallest part (this means the splitting level) and the file size, not on the size in general. This means that for time estimation the ratio between the size of the defect or the size of the analysed feature of a FRP part to the size of the whole part has to be considered.

Size [MB]	Runtime [min]	Resolution [µm]
81	4	0,7
724	11	29,9

Table 2: Runtime and size of test files

3 Conclusion

Even if some defects are visible without using analysis tools, it is absolute necessary for automatic defect detection and analysis of fibre reinforced plastics to develop adequate analysis tools. Such analysis tools can offer not only qualitative information, but also quantitative information, like the size of a defect or orientation of fibres in degrees.

The developed 3D texture analysis tool is one step in this direction. The advancement of this tool and the development of other automatic tools will be an important contribution in order to bring fibre reinforced plastics in large-scale production.

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