Image Fusion in X-Ray Differential Phase-Contrast Imaging

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ABSTRACT

Phase-contrast imaging is a novel modality in the field of medical X-ray imaging. The pioneer method is the grating-based interferometry which has no special requirements to the X-ray source and object size. Furthermore, it provides three different types of information of an investigated object simultaneously – absorption, differential phase-contrast and dark-field images. Differential phase-contrast and dark-field images represent a completely new information which has not yet been investigated and studied in context of medical imaging. In order to introduce phase-contrast imaging as a new modality into medical environment the resulting information about the object has to be correctly interpreted. The three output images reflect different properties of the same object the main challenge is to combine and visualize these data in such a way that it diminish the information explosion and reduce the complexity of its interpretation.

This paper presents an intuitive image fusion approach which allows to operate with grating-based phase-contrast images. It combines information of the three different images and provides a single image. The approach is implemented in a fusion framework which is aimed to support physicians in study and analysis. The framework provides the user with an intuitive graphical user interface allowing to control the fusion process. The example given in this work shows the functionality of the proposed method and the great potential of phase-contrast imaging in medical practice.

Keywords: X-ray imaging, grating interferometer, differential phase-contrast, Talbot-Lau interferometer, image fusion, visualization

1. INTRODUCTION

The concept of X-ray phase-contrast imaging has been investigated for several decades, but its applicability in the medical environment has become possible only since last few years. This work focuses on the grating-based interferometry approach,[1] also known as Talbot-Lau interferometry. Compared to other X-ray phase-contrast imaging approaches – interferometric methods,[2–4] free-space propagation,[4–6] crystal-based[4] – the interferometry approach has no special requirements to the X-ray source and object size. Furthermore, the grating-based method provides three different types of information of an investigated object simultaneously. Compared to the conventional X-Ray imaging output which is the absorption image (*AMP*), the grating-based approach extracts additionally differential phase-contrast (*DPC*) and dark-field images (*DCI*). *DPC* as well as *AMP* gives the information about material properties of the object under study and *DCI* provides the information about the local scattering of the object.[7] However, before bringing phase-contrast grating-based imaging into clinical use it is required to provide an interpretation of the obtained data. The three output images represent different information about the same object, which increases the complexity of interpretation and burdens a physician significantly. The problem of high importance here is to provide a tool to visualize and combine these data which would help physician to compare new information with the known one (absorption image) and therefore to learn a new modality. This work presents a novel solution enabling a physician to combine the *AMP*, *DPC* and *DCI* information in a single image by a smart weighting. The proposed approach allows to adjust the parameters

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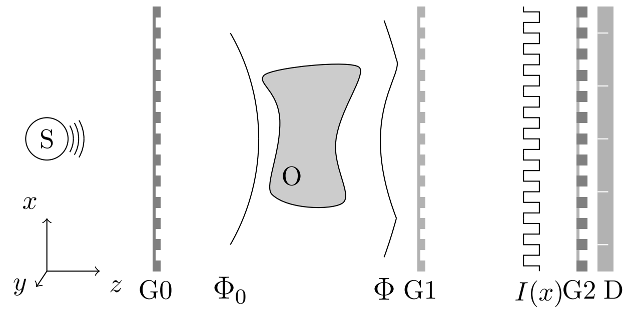

Figure 1. Basic setup of a grating-based interferometer for phase-contrast imaging with X-rays where S denotes the source, $G0$ source grating, Φ_0 initial wave-front, O object, Φ deformated wave-front, $G1$ phase grating, $I(x)$ interference pattern (fringes), $G2$ analyzer grating and D the detector.

easily by an intuitive user interface. Furthermore to simplify the interpretation and to make information more obvious, a smart colorization is presented. Section 2 gives a brief introduction to the grating-based phase-contrast imaging. Section 3 presents the novel approach of combining grating-based images and the details of implementation are shown in section 4.

2. GRATING-BASED PHASE-CONTRAST IMAGING

In conventional X-ray imaging, the X-rays penetrating the object under study are assumed not to be refracted. The contrast is obtained by differences in the absorption cross section.[8] Indeed the X-rays are refracted and this refraction characterizes the object. Due to the magnitude of a few micro-radians, refraction angles cannot be measured by a detector directly. Existing phase-contrast approaches are based on the observation of indirect effects, e.g., interference caused by change of phase and consequent computation of refraction characteristics.

The Talbot-Lau interferometer[1] exploits the Talbot effect discovered in *1836*. It states that a coherent illumination of a periodic structure leads to repetitive intensity patterns in certain distances, so called odd fractional Talbot-distances. To observe this effect the hardware setup of the interferometer (Fig. 1) consists of two gratings – a phase grating G1 and an analyzer grating G2. G1 acts as a phase mask imprinting a periodic phase modulation onto the X-ray wave-front Φ.[9] This modulation leads to a periodic interference pattern (also called fringes) downstream towards the G2 grating. Deformations of the initial wave-front result in a local displacement of the fringes which corresponds to the first derivative of the wave-front Φ in x-direction[1] (differential phase-contrast).

Since the fringes are in the range of few microns it is difficult to measure them while having a large field of view. Therefore, an absorption grating G2 is required which acts as an analyzer grating. This grating has the same periodicity and orientation as the fringes.[10] By shifting grating G2, local fringe positions are translated into intensity variations which encode information about absorption, phase shift and dark-field. This method is known as phase-stepping technique.[10]

In order to use a conventional medical X-ray tube with a finite focal spot size, a third grating G0 is required (Fig. 1). G0 is placed between the X-ray source and object. It splits the large source in many smaller sources which are mutually incoherent but the coherence of each single source is large enough to produce interferences.[1]

3. INNOVATIVE METHOD

In contrast to the conventional X-ray imaging the grating-based imaging approach is able to provide multiple outputs. All together these images represent not only X-ray attenuation which can be interpreted as material density, but show as well enhanced borders inside the object and scattering of the material. In medical applications, this is of high relevance for example in oncological investigations and treatment planning. However, this leads to a cognitive overload for the physician with abundance of essential information of the same object distributed among different images. This paper presents an intuitive image fusion approach to combine these

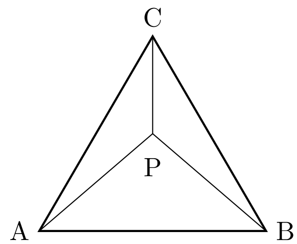

Figure 2. Barycentric coordinates: point P is a weighted sum of the vertices A, B and C. The weighting coefficients form a triple of numbers (α, β, γ) which is called barycentric coordinate of P.

three sources of information to correlate it pixel by pixel and on the other hand to reduce the information flood and complexity.

The proposed method aims at merging multiple grating-based images into a single one. The image originating from three other images by fusion can be represented as a weighted sum:

$$P = \alpha A + \beta B + \gamma C \tag{1}$$

where $P \in \mathbb{R}^{height \times width}$ is a resulting image, A, B and $C \in \mathbb{R}^{height \times width}$ correspond to the images AMP, DPC and DCI respectively. α, β, γ are the weighting coefficients.

The major problem in computing the weighting coefficients of the components for this application is to keep them easily and clearly adjustable for physicians. For this purpose a barycentric coordinate system on a triangle is considered to be a successful solution. Barycentric coordinates are often used in 3D computer graphics to interpolate colors inside a triangular mesh of an object surface. Barycentric coordinates are triples of numbers (α, β, γ) corresponding to the masses placed in the vertices of a reference triangle. These masses then determine a point P, which is the geometric centroid of the three masses and is defined with coordinates (α, β, γ). Accordingly the vertices of the triangle themselves have coordinates $(1, 0, 0), (0, 1, 0), (0, 0, 1)$.[11]

To find coordinates of an arbitrary point assume three given points A, B and C on a hyperplane, forming a triangle (Fig. 2). Every point P on the hyperplane can be expressed as a linear combination of A, B and C:

$$\begin{aligned} P &= \alpha A + \beta B + \gamma C \\ \text{st.} \quad & \alpha + \beta + \gamma = 1 \end{aligned} \tag{2}$$

where (α, β, γ) are the barycentric coordinates of P. The magnitudes of α, β and γ are proportional to the signed areas of the subtriangles PBC, PCA and PAB. Thus they can be computed in the following way:

$$\alpha = 1 - \beta - \gamma \tag{3}$$

$$\beta = \frac{(x_A - x_C)(y_P - y_C) - (y_A - y_C)(x_P - x_C)}{(x_B - x_A)(y_C - y_A) - (y_B - y_A)(x_C - x_A)} \tag{4}$$

$$\gamma = \frac{(x_B - x_A)(y_P - y_A) - (y_B - y_A)(x_P - x_A)}{(x_B - x_A)(y_C - y_A) - (y_B - y_A)(x_C - x_A)} \tag{5}$$

Applied to the considered problem of weighting coefficients the vertices of the triangle in barycentric coordinate system are to be the grating-based images AMP, DPC and DCI. Each point inside the triangle corresponds to the specifically fused images with the weights $0 \leq \alpha, \beta, \gamma \leq 1$, computed by the equations (3) to (5).

The described case of barycentric coordinates considers α, β and γ to be scalars what leads the resulting image to be grayscale. The three grating-based images merged in such a way reduce to a highly informative image. Obviously this image does not allow to differentiate the source of the information and thus to distinguish properties of the objects with sophisticated structure and microstructure. This can be resolved by introducing colors. According to equation (1) the colorspace should be additive, such as RGB, and the weighting coefficients are therefore vectors. Each of the grating-based images could be assigned to a specific color channel and the resulting image would represent the colorful fusion of three original images.

Thus, the general case of image fusion can be described by the equation below:

$$P^*_{y,x} = \alpha \begin{pmatrix} 1 \\ 1 - c_A \\ 1 - c_A \end{pmatrix} A_{y,x} + \beta \begin{pmatrix} 1 - c_B \\ 1 \\ 1 - c_B \end{pmatrix} B_{y,x} + \gamma \begin{pmatrix} 1 - c_C \\ 1 - c_C \\ 1 \end{pmatrix} C_{y,x} \tag{6}$$

where $P^* \in \mathbb{R}^{height \times width \times 3}$ is the resulting colored image and $x \in \{0, \ldots, width - 1\}$, $y \in \{0, \ldots, height - 1\}$ indexes of the pixels. The parameters $c_A, c_B, c_C \in \{0, 1\}$ denote the grayscale or color case of the fusion. Setting them to 0 simultaneously results in a grayscale image. Assigning 1 to any of these coefficients switches on the corresponding color channel. Independence of these parameters of each other gives the opportunity to apply color mode to input images.

The presented image fusion approach can be extended to an arbitrary number n of images. In this case the triangle is replaced by a (convex) polygon with n vertices. The weighting coefficients can be computed by the generalized barycentric coordinates on polygons.[12]

4. IMPLEMENTATION AND RESULTS

The proposed method is implemented as a prototype in the in-house phase-contrast image fusion software. To start the procedure of studying results of phase-contrast investigation, the three images *AMP*, *DPC* and *DCI* should be loaded. In order to provide a physician with a suitable visualization tool, the prototype includes preprocessing filters such as different kinds of windowing, normalization, etc., which can be applied to each of the images.

Especially useful in the case of phase-contrast imaging transformations – absolute value of *DPC* intensities and $1 - DCI_{y,x}$ – are implemented in the prototype as well. These transformations make sure that areas without an object in all the images have the lowest intensity values. The application of the special transformations result in an enhancement of visual contrast.

Figure 3 displays grating-based phase-contrast images of a lung of a mouse. The data was acquired ex-vivo. The top row shows the original *AMP*, *DPC* and *DCI* images of the lung and in the bottom row the enhanced images which are used later to demonstrate the fusion approach. The described fusion technique is implemented in the form of a triangular user interface controller as shown in Fig. 4. To adjust weights the user moves the marker using a mouse, each position of a marker corresponds to a specific set of α, β, γ coefficients computed in real time. The resulting fused image is updated simultaneously. The prototype also provides the functionality to change the grayscale and color representation of each image independently. Figure 5 shows an example of grating-based phase-contrast image fusion. The original *AMP*, *DPC* and *DCI* images are fused with weights corresponding to a position of the marker at point $P = (\alpha = 0.16,\ \beta = 0.16,\ \gamma = 0.68)$ (Fig. 4). Figure 5 shows on the left the grayscale and on the right side the color mode of fusion. These images show the main advantage of the phase-contrast imaging and the proposed fusion approach. The *AMP* of the lung shows conventional absorption information, lobes anatomy can be observed. The boundaries of structures are clearly visible on the *DPC*. This image can be combined with *AMP* which would lead to enhancement of local structures and consolidations. On the *DCI* the strong local scattering in the superior lobe of the lung is observed, which is probably caused by alveoles. This effect is not observed all over the lung supposedly because of the drying process. This specific example visually demonstrates that the three grating-based output images altogether contain important information about the object. For better understanding and interpretation a fusion of these images is essential as the fused image allow to observe all the information simultaneously. The fusion in a color mode at the same time keeps the source of the information.

5. CONCLUSION AND OUTLOOK

The grating-based phase-contrast imaging approach is a new modality in the field of medical X-ray imaging. It provides three different types of information of an investigated object simultaneously – absorption (*AMP*), differential phase-contrast (*DPC*) and dark-field information (*DCI*). *DPC* and *DCI* are completely new information which requires a correct interpretation and a suitable tool for investigation. An intuitive image fusion

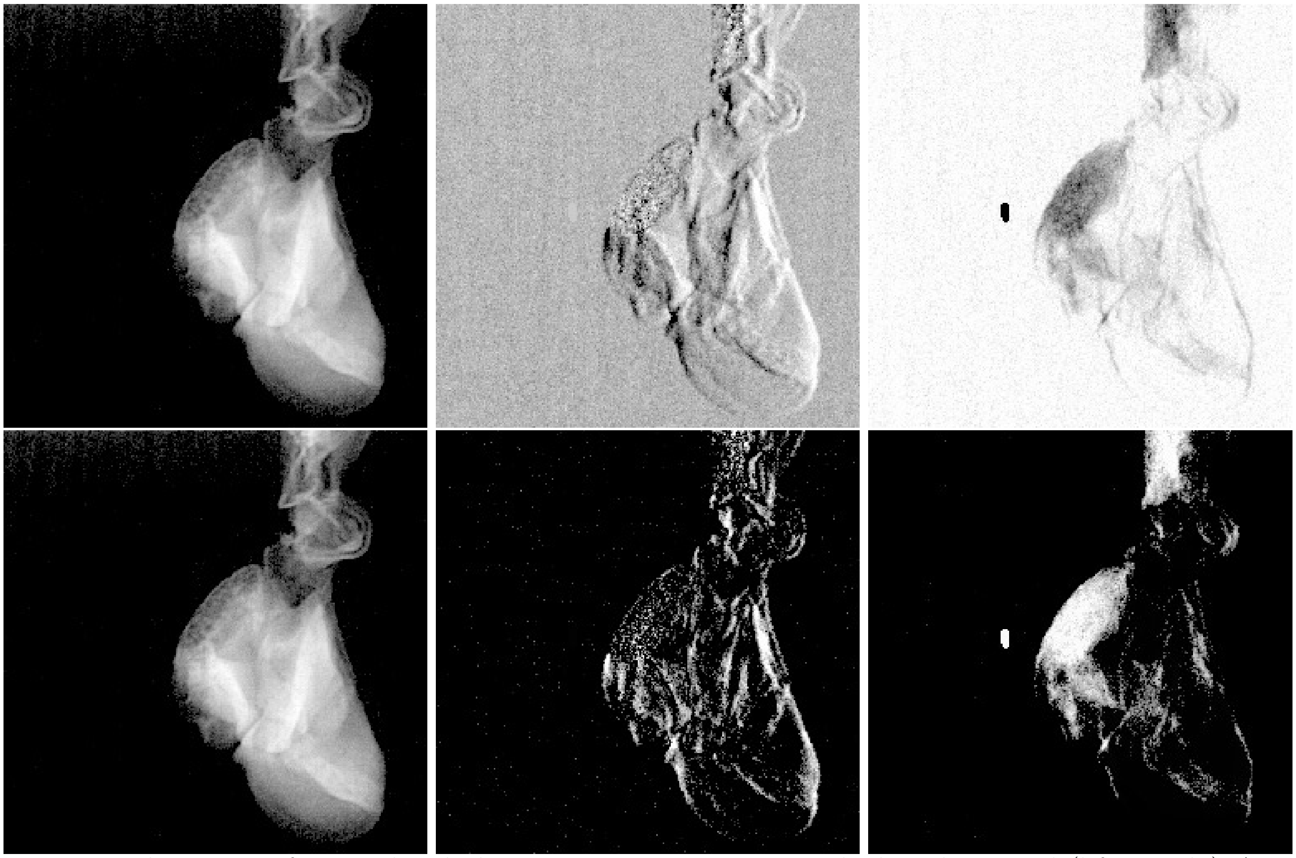

Figure 3. Enhancement of grating-based phase-contrast images: Top row displays the original (left to right) AMP, DPC and DCI images of a lung of a mouse; bottom row shows the enhanced images as they are used for the further demonstration of the fusion approach (AMP, $\|DPC\|$ and $1 - DCI_{y,x}$).

approach was presented in this paper. Its purpose is to combine information of these three different kinds in one single image to correlate the information pixel by pixel. On the other hand to reduce the information flood and complexity of reading and interpreting the visual data. The impressive example demonstrating the proposed fusion framework shows the power of the method.

In the nearest future a collaboration with physicians is planned in order to study and investigate phase-contrast imaging in medical practice by means of the proposed fusion framework.

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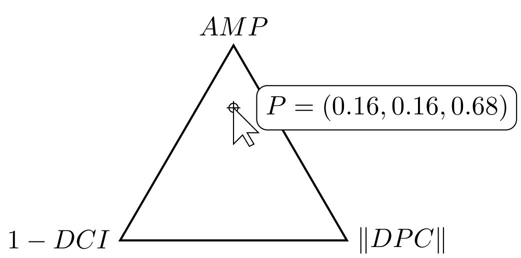

Figure 4. Graphical user interface controller: Fusion coefficients are adjusted by moving the marker inside the triangle.

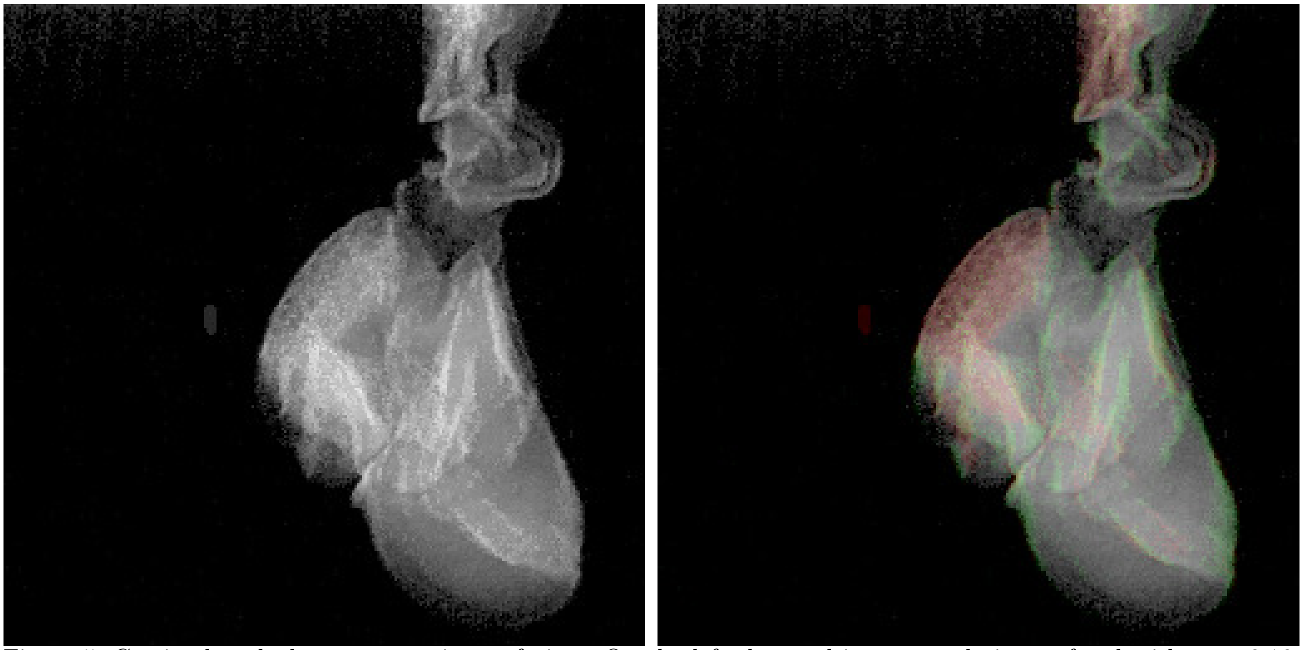

Figure 5. Grating-based phase-contrast image fusion. On the left the resulting grayscale image fused with $\alpha = 0.16$, $\beta = 0.16$ and $\gamma = 0.68$. On the right the color fused image: *DPC* assigned to the green channel, *DCI* to the red one and the *AMP* image is visualized in a grayscale mode.

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