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# PROGRESS IN REAL-TIME PHOTOACOUSTIC IMAGING USING OPTICAL ULTRASOUND DETECTION

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# Progress in real-time photoacoustic imaging using optical ultrasound detection

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## Abstract

Optical phase contrast full field detection in combination with a CCD-camera can be used to record acoustic fields. This allows to obtain two-dimensional photoacoustic projection images in real-time. The present work shows an extension of the technique towards full three-dimensional photoacoustic tomography. The reconstruction of the initial three dimensional pressure distribution is a two step process. First of all, projection images of the initial pressure distribution are acquired. This is done by back propagating the observed wave pattern in frequency space. In the second step the inverse Radon transform is applied to the obtained projection dataset to reconstruct the initial three dimensional pressure distribution. An experiment is performed using a phantom sample which mimics the properties of biological samples to show the overall applicability of this technique for real-time photoacoustic imaging.

## Introduction

Charge coupled device (CCD) cameras as acoustic sensors in photoacoustic imaging (PAI) have parallel detection capabilities but at very limited camera frame rate. Therefore, an alternative approach to speed up the data acquisition is to use the spatial information content of a single captured image at a certain time instead of using time resolved signals recorded at defined detector positions. Under certain conditions a single captured image of the acoustic wave pattern contains all information to reconstruct a two-dimensional (2D) photoacoustic projection image of the initial pressure distribution. The proof of principle for use of a CCD camera in real-time PAI has already been demonstrated [1-2].

The method proposed here uses an interferometric setup for detecting pressure induced variations of density and refractive index in a coupling medium around the imaged object. If the pressure induced optical phase shift of the probe laser beam is much smaller than $\pi$, interferometry delivers a linear relation between the detected light intensity and the pressure values. This relationship is based on a linear dependence of the change of optical refractive index on acoustic pressure. The phase contrast technique, developed by Fritz Zernike, uses the interference between diffracted and non-diffracted light in an optical imaging setup and also delivers a contrast in the captured images which is proportional to the pressure amplitude [3-4].

The gained information about the optical phase shift is therefore a representation of the pressure field at a given time, projected or integrated along a certain direction. This method is related to the concept of using integrating line detectors in PAI [6-8]. Instead of a single detector that measures time resolved signals from a single line detector (a free or guided light beam), full field detection (FFD) uses a detector array, interrogating the integrated pressure at a given time from a 2D array of line detectors. To obtain the initial three dimensional (3D) pressure distribution, first of all the acoustic wave pattern has to be captured from several directions. Each individual pattern is used to calculate a 2D projection of the pressure distribution at time zero. The second step is to apply the inverse Radon transform (RT) to the projection dataset calculated in the previous step, to obtain the initial 3D pressure distribution.

## Measurement setup

The experimental setup for capturing a picture of the acoustic wave pattern (the phase object) is shown in Fig. 1. Laser pulses with 10ns pulse duration coming from the frequency doubled output (532 nm) of a 10Hz Nd:YAG laser system were used for photoacoustic excitation. The sample was illuminated from bottom-up with a fluence of 20 mJ/cm². The sample itself was only slightly dipped in water for acoustic coupling and positioned in the rear focal plane (object plane) of the Fourier transforming lens (L2). The pulsed probe laser beam coming from a diode pumped solid state laser system ($\lambda_{Det}$=527 nm, $t_{puls}$=8 ns) was collimated and expanded to a beam diameter which was about two times the size of the sample. This ensured that the detection aperture is sufficiently large to capture the outgoing acoustic waves coming from the optically absorbing regions inside the sample.

Due to interaction of the acoustic and optical fields (elasto-optic interaction) the latter attains a phase variation proportional to the pressure integrated along the probe beam path. This is converted into a measurable intensity modulation by arranging an optical signal processing element (PP: phase plate) in the Fourier plane of the first imaging lens (L2). Like in optical phase contrast microscopy an additional relative phase shift of either plus or minus $\pi/2$ between the non-diffracted and diffracted portions of the probe laser beam leads to constructive or destructive interference between both parts. This results in a so called positive or negative phase contrast image. The lens L3 is arranged in a way that its rear focal plane and the phase plate coincide, producing a reversed image of the phase object on the CCD element of the camera. Snapshots of the pressure distribution were taken with a CCD camera (pco.2000s, 14 Bit dynamic range) at certain time delay with respect to the excitation laser pulse. The time delay was adjusted by using a delay generator. The spatial resolution of the detection system is determined by the optical magnification $M_O$ and the pixel pitch $S_P$ of the CCD element. From that follows

$$\Lambda_{min} = 2 \cdot \frac{S_P}{M_O} = 2 \cdot \frac{14.8\mu m}{0.45} \approx 66\,\mu m$$
$$\Rightarrow f_{max} \approx 23MHz$$

where $\Lambda_{min}$ and $f_{max}$ denotes the smallest detectable wavelength and the upper cut-off frequency of the current detection setup. In principle, the resolution is adjustable with $M_O$. The natural limit is the optical diffraction limit determined by the wavelength and the numerical aperture of imaging system. Note that the acoustic field is integrated along the propagation direction of the probe laser beam. Therefore, also the depth of field (~ 8 mm) of the optical imaging system is an important parameter.

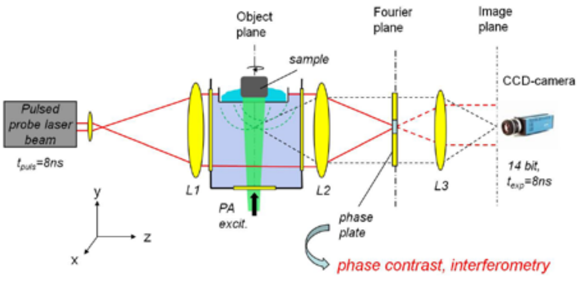


Fig. 1 Phase contrast detection setup

## Experiments

To verify that the proposed method is suitable for real-time PAI an experiment was conducted using a phantom sample containing black horse hair bristles with diameters ranging from 250-300µm embedded at a depth of 5 mm in turbid gelatin forming the letters "PA" (see inset in Fig. 2). Before reconstruction, wave pattern images were corrected by subtracting the corresponding background image. Each projection image was obtained in real-time (without averaging). To obtain the 3D image 200 projection images were recorded over a full rotation. Consequently, the recording time of the 3D data takes just 40 seconds (for wave pattern images and background images).

The reconstruction of the initial three dimensional pressure distribution $p_{t=0}(x,y,z)$ is a two step process. First of all, projection images of the initial pressure distribution $p^{\alpha}_{t=0}(x,y)$ are acquired. This is done by back propagating the observed wave pattern $p^{\alpha}_{t=T_0}(x,y)$ in frequency space or rather by convolving the captured acoustic wave pattern with the Green function of the 2D wave equation. The 2D Fourier reconstruction algorithm is given by

$$p^{\alpha}_{t=0}(x,y) = FT^{-1}[\,FT[\,p^{\alpha}_{t=T_0}(x,y)] \cdot 2 \cdot cos(\omega \cdot T_0)\,],$$

where the cosine function denotes a time-propagator in frequency space causing forward as well as backward propagation of the acoustic wave pattern and $T_0$ is the traveling time of the acoustic wave which is equal to the delay time between probe and excitation laser pulse. In the second step the inverse Radon transform (IR) is applied to the obtained projection dataset to reconstruct the initial three dimensional pressure distribution. Maximum amplitude projection images of the obtained 3D image are shown in Fig. 2.

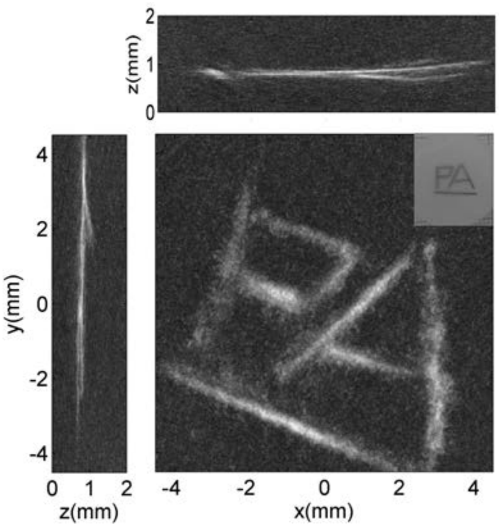


Fig. 2 Maximum amplitude projection images in x,y and z direction. The inset shows a photograph of the phantom sample. For the photograph the top layer of turbid gelatin was removed.

## Conclusion

In conclusion, the presented technique provides real time 2D and fast 3D photoacoustic imaging using a purely optical, parallel detection method. It combines the advantages of optical detection with the possibility to acquire the required high amount of data within a relatively short time using parallel detection with a CCD camera.

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